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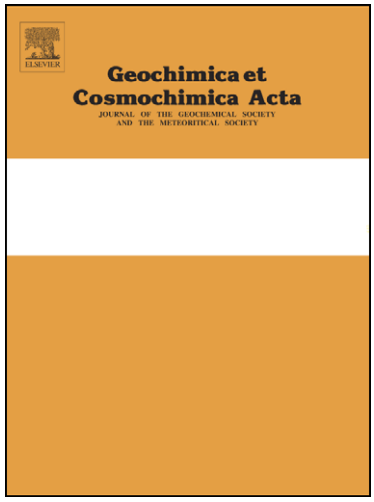

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The relationship between CK and CV chondrites

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ABSTRACT

CK chondrites are highly oxidized meteorites containing abundant magnetite and trace amounts of Fe,Ni-metal. Although the group is predominately composed of equilibrated meteorites (types 4 to 6), in recent years a significant number of new samples have been classified as being either CK3 or CK3-anomalous. These unequilibrated CKs often display a close affinity with members of the CV oxidized subgroup. CKs and CVs (oxidized subgroup) may therefore form a continuum and by implication could be derived from a single common parent body. To investigate the relationship between these two groups a detailed study of the oxygen isotope composition, opaque mineralogy and major and trace element geochemistry of a suite of CV and CK chondrites has been undertaken. The results of oxygen isotope analysis confirm the close affinity between CV and CK chondrites, while excluding the possibility of a linkage between the CO and CK groups. Magnetites in both CV and CK chondrites show significant compositional similarities, but high Ti contents are a diagnostic feature of the latter group. The results of major and trace element analysis demonstrate that both CV and CK chondrites show overlapping variation. Supporting evidence for a single common source for both groups comes from their similar cosmic-ray exposure age distributions. Recent reflectance spectral analysis is consistent with both the CVs and CKs being derived from Eos family asteroids, which are believed to have formed by the catastrophic disruption of a single large asteroid. Thus, a range of evidence appears to be consistent with CV and CK chondrites representing samples from a single thermally stratified parent body. In view of the close similarity between CV and CK chondrites some modification of the present classification scheme may be warranted, possibly involving integration of the two groups. One means of achieving this would be to reassigned CK chondrites to a subgroup of the oxidized CVs. It is recognized that a full evaluation of this proposal may require further study of the still poorly understood CK3 chondrites.

1. INTRODUCTION

Carbonaceous chondrites remain one of our principal sources of information about the earliest stages of solar system evolution. Detailed studies continue to focus on a variety of components within these meteorites, including: refractory inclusions (Thrane et al., 2006; Krot et al., 2008), presolar grains (Verchovsky et al., 2006; Marhas et al., 2007), organic material (Pizzarello et al., 2006), silicate chondrules (Libourel and Krot, 2007; Chaussidon et al., 2008). These materials were formed in diverse environments, ranging from pre-nebular to asteroidal (McSween et al., 2006). More than any other major class of meteorites, carbonaceous chondrites show evidence for extensive secondary processing of their primary constituents (Jones and Brearley, 2006; Krot et al., 2006). However, whether this took place primarily in a nebular or asteroidal setting has been a longstanding debate in meteoritical science (Arrhenius and Alfvén, 1971; Kerridge et al., 1979; Bischoff, 1998; Krot et al., 1998; Young et al., 1999; Hsu et al., 2006).

Carbonaceous chondrites typically have whole rock refractory lithophile abundances ≥1 x CI, oxygen isotope compositions that plot below the terrestrial fractionation line, and generally contain refractory inclusions (Kallemeyn et al., 1991; Weisberg et al., 2006). The present subdivision of carbonaceous chondrites into eight principal groups: CI, CM, CR, CO, CV, CK CH and CB (Weisberg et al., 2006) is made on the basis of a diverse range of criteria, some of which relate to differences between the various primary constituents i.e. size-range of chondrules and refractory inclusions, and others which reflect the degree of secondary alteration. As noted by Weisberg et al. (2006), there is a common assumption in meteorite taxonomy that all meteorites in the same group are from a common asteroidal parent body. However, in the case of the carbonaceous chondrites this linkage is at best poorly established. Thus, the CV and CK groups characteristically contain large chondrules and refractory inclusions, whereas those in the CO and CM groups are significantly smaller.

This important difference is currently regarded as being due to aerodynamic sorting in the solar nebula, and hence predates the onset of parent body processes (Cuzzi et al., 2001; Liffman, 2005). In contrast, it has been argued that the mineralogical and oxygen isotope variability among the CV, CM and CI groups is essentially the result of parent body alteration (Young et al., 1999). Thus, the characteristic differences between carbonaceous chondrite groups probably results from a combination of both nebular and parent body processes.

In this paper we examine the relationship between two carbonaceous chondrite groups, the CVs and CKs, which display many similar features and hence are collectively known as the CV-CK clan (Weisberg et al., 2006). However, the exact nature of this relationship is poorly understood (Weisberg et al., 2006). The general view appears to be that, while both groups show many similar characteristics, they were drawn from somewhat different nebular reservoirs and subsequently became incorporated into distinct parent bodies, each of which had a unique alteration history (Kallemeyn et al., 1991; Hirota et al., 2002a,b). In contrast, it has been suggested that both groups may be samples from a single common parent body (Greenwood et al., 2003, 2004). Unlike other carbonaceous chondrite groups which contain only unequilibrated material (type 1 to 3), CK chondrites are dominated by equilibrated meteorites (type 4 to 6), although type 3 CKs are also recognized. If CVs and CKs were derived from a single parent body it would represent a situation equivalent to that which is believed to exist amongst the ordinary chondrites, in which equilibrated and unequilibrated meteorites appear to form a continuum (type 3 to 6) within each of the main groups (H, L, LL). This relationship is commonly taken as evidence that ordinary chondrite parent bodies were thermally stratified: the so-called onion-shell model (Wood, 2003; Trieloff et al., 2003). In examining the relationship between CV and CK chondrites our specific aim is to investigate the possibility that they were derived from the same parent body source. Our more general aim is to examine the relationship between the taxonomic division of meteorites into

groups and clans (Weisberg et al., 2006) and to assess the extent to which these have value in identifying single or multiple parent body sources.

In this paper we do not attempt to give a comprehensive overview of all aspects of the CV and CK groups. A summary description of each group is given in sections 3.1. and 3.2. Instead, we focus in detail on three important features of both groups which shed new light on their origin and interrelationships. Firstly, in order to assess their nebular and subsequent asteroidal histories we present new data on the oxygen isotope composition of CV and CK chondrites. Secondly, we look in detail at the opaque mineralogy of both groups. CV (oxidized subgroup) and CK chondrites contain significant modal magnetite, indicating that both underwent alteration in a highly oxidizing environment. We therefore look in detail at the composition of magnetite in both groups as a means of understanding whether they experienced similar, or differing alteration histories. Finally, we present new bulk compositional data obtained by ICP-MS in order to evaluate the extent to which both groups differ in terms of either their major or trace element compositions.

2. ANALYTICAL TECHNIQUES

2.1 Oxygen isotopes

Oxygen isotope analysis was carried out at the Open University using an infrared laser fluorination system (Miller et al., 1999). Violent ejection of powders from sample wells can occur when dealing with volatile-rich material, such as carbonaceous chondrites. To avoid this problem all analyses were obtained on whole-rock samples (0.5-2 mg) that were heated progressively in the presence of BrF_5 for periods lasting up to 1 hour. After fluorination the O_2 released was purified by passing it through two cryogenic nitrogen traps and over a bed of heated KBr. O_2 was analyzed using a Micromass Prism III dual inlet mass spectrometer. Analytical precision (1σ), based on replicate analysis of international (NBS-28 quartz, UWG-

2 garnet) and internal standards, is approximately ±0.04‰ for $\delta^{17}O$; ±0.08‰ for $\delta^{18}O$; ±0.024‰ for $\Delta^{17}O$ (Miller et al., 1999). All sample powders analyzed in this study were drawn from larger homogenized aliquots, obtained by crushing interior whole rock chips, with a minimum mass of about 100 mg. However, even despite these procedures, since carbonaceous chondrites are highly heterogeneous mixtures of high and low temperature components, precision is often less than that obtained on international standards. The precision (1σ) quoted for individual meteorite samples analyzed in this study is based on replicate analyses. For ease of comparison with previous oxygen isotope studies of carbonaceous chondrites (Clayton and Mayeda, 1999) $\Delta^{17}O$ has been calculated as:

$$\Delta^{17}O = \delta^{17}O - 0.52\ \delta^{18}O.$$

2.2 Mineral analysis

Analysis of magnetites was undertaken on Allende (CV_{oxA}), Vigarano (CV_R), Watson 002 (CK3), Sleeper Camp 006 (CK4), DaG 250 (CK4/5), DaG 275 (CK4/5) using a wavelength dispersive Cameca SX-50 electron microprobe at the Natural History Museum, London. Operating parameters were 20kV, 20nA and a tightly focused spot size. Standards included metals (V, Cr, Mn, Co, Ni); oxides (Al_2O_3, TiO_2, Fe_2O_3) and silicates (Mg and Si from Eagle Station Olivine, Ca from wollastonite). Matrix corrections were performed using the Cameca version of the PAP PhiRhoZ programme.

2.3 Major and trace element analysis

Major and trace element analysis was undertaken at the Open University using a HP7500a ICP-MS. Powder or chips of CV and CK meteorites, along with reference materials BHVO-2, BCR-1, UBN and JP-1, were weighed into screw top Teflon beakers. Each sample was dissolved in 4 ml of HF:$HClO_4$ at 120ºC and this digestion was followed by three

evaporation steps with $HClO_4$, HCl and HNO_3. The dried down residues were then dissolved in HNO_3 and MQ-water to obtain a 10% HNO_3 (by weight) solution. Aliquots of these solutions were further diluted in order to obtain two 2% HNO_3 solutions for each sample, with dilution factors of ca. 1,000,000 and 10,000 for major and trace element analyses respectively. Sample intensities were calibrated against 8 dissolutions of 4 external standards (BHVO-2, BCR-1, UBN and JP-1). Procedural blanks were also run. The HP7500A ICP-MS was ran at 1350W and tuned for maximum sensitivity, while keeping the oxide production to a minimum ($^{248}ThO/^{232}Th<0.5\%$). "Synthetic solutions", containing a know amount of elements such as Mg and Na, were run at the beginning and end of each ICP-MS session to monitor and calibrate the production of interfering polyatomic ions on the mass of interest. For example, the formation of $^{25}Mg^{40}Ar$ and $^{23}Na^{40}Ar$ were measured in order to accurately analyze ^{63}Cu and ^{65}Cu, similarly the effect of $^{16}O^{53}Cr$ and $^{16}O^{55}Mn$ on ^{69}Ga and ^{71}Ga respectively, were also assessed. The reproducibility of the dissolution technique and the efficiency and accuracy of the calibration strategy are assessed in Table 1, where the analyses of 6 different dissolutions of Allende (5-20 mg) are reported against a compilation of literature data for Allende (Bland et al., 2000 and references therein). We note that Ti and Zn fall somewhat below the literature value and hence caution is required in respect of these particular elements when evaluating the data for CV and CK samples measured in this study.

3. CHARACTERISTIC FEATURES OF CV AND CK CHONDRITES

3.1 CV chondrites

CV chondrites are a heterogeneous group of meteorites characterized by the presence of large chondrules and refractory inclusions, enclosed in a relatively coarse-grained matrix of predominantly FeO-rich olivine (Brearley and Jones, 1998) (Fig. 1a). All known CVs are of petrologic type 3 and consequently the group is sometimes also referred to as the CV3

chondrites. Following the original definition of the group by Van Schmus (1969) the CV chondrites were subdivided by McSween (1977) into reduced and oxidized subgroups on the basis of metal vs. magnetite abundances, and Ni contents of sulphide minerals. In the reduced subgroup (CV_R) metal predominates over magnetite, whereas in the oxidized subgroup metal is either absent, or present in only trace amounts (Krot et al., 1995). On the basis of secondary mineral assemblages the oxidized subgroup was further divided into Allende-like (CV_{oxA}) and Bali-like (CV_{oxB}) subgroups (Weisberg et al., 1997). The presence of phyllosilicates in the matrices of CV_{oxB} subgroup samples indicates that these meteorites experienced aqueous alteration, whereas phyllosilicates are largely absent from members of the CV_{oxA} subgroup (Krot et al., 1995, 1998, 2005). In contrast, CV_{oxA} chondrites experienced intense Fe-alkali-halogen metasomatism leading to the formation of a complex assemblage of secondary minerals including: nepheline, sodalite, andradite, grossular, wollastonite, kirschsteinite and hedenbergite (Kimura and Ikeda, 1995; Krot et al., 1995, 1998, 2005). The dominant phase within the matrices of CV chondrites is FeO-rich olivine, which varies considerably in composition from one member of the group to another (Krot et al., 1995; Brearley and Jones, 1998). The widest variation in matrix olivine compositions is seen in the CV_{oxB} chondrite Kaba ($Fa_{10\text{-}90}$), with those in Allende (CV_{oxA}) being the most homogeneous ($Fa_{38\text{-}55}$) (Krot et al., 1995).

Despite the lithological diversity displayed by the CV chondrites there is strong petrographic evidence to suggest that all of these subgroups are samples from a single heterogeneous asteroid. Thus, the Vigarano CV_R chondrite contains lithic clasts of CV_{oxB}-like material (Krot et al., 2000), while Mokoia contains both CV_{oxB} and CV_{oxA}-like lithologies (Krot et al., 1998). It was noted by McSween (1977) that the Leoville chondrite contains centimeter-sized areas comprising either exclusively oxidized or reduced material. McSween (1977) suggested that this was evidence in favour of post-accretional brecciation

and mixing prior to consolidation to form the final meteorite. In keeping with this suggestion, Krot et al. (1995) point out that four CV chondrites are known to contain solar wind gases (Vigarano, Mokoia, Arch and Allende) and hence are best regarded as being regolith breccias. Studies of induced thermoluminescence indicate that all known CV chondrites, are of relatively low petrographic grade ranging from 3.0 to 3.3 (Guimon et al., 1995). The ubiquitous preservation of melilite in CV CAIs (Brearley and Jones, 1998) also indicates that most members of the group are of a relatively low metamorphic grade. In contrast, a recent study of the maturity of matrix organic matter as determined by Raman spectroscopy has come to different conclusions (Bonal et al., 2006) and suggests that Grosnaja, Mokoia, Bali, Axtell and Allende are grade 3.6 or higher. One possible explanation for this apparently contradictory evidence is that the silicate and organic components are decoupled with respect to thermal metamorphism, a situation that is also seen in a number of CO chondrites (Pearson et al., 2007). The CV samples analyzed in this study are listed in Table 2a.

3.2 CK chondrites

CK chondrites are highly oxidized meteorites containing abundant magnetite and trace amounts of Fe,Ni-metal (Kallemeyn et al., 1991; Noguchi, 1993; Geiger and Bischoff, 1995) (Fig. 1b-1h). The matrices of CK chondrites are characteristically dominated by the presence of equilibrated, Ni-rich olivines (NiO ~0.5 wt%) with a composition close to $Fa_{31\pm3.}$ (Kallemeyn et al., 1991; Noguchi, 1993 Geiger and Bischoff, 1995). A further characteristic feature of CK chondrites is the presence of large, rounded magnetite-rich objects up to 1mm in diameter (Geiger and Bischoff, 1995). In these objects magnetite, often containing apatite and sulphide inclusions, displays prominent exsolution lamellae of ilmenite and spinel (Fig. 1f) (Geiger and Bischoff, 1995).

When first defined, all recognized members of the CK group were equilibrated meteorites (types 4 to 6) (Fig. 1e,f,g). The sole exception to this was Ningqiang, which has subsequently been reclassified as C3-ungrouped (Met. Bull 65). The CKs were thus in marked contrast to all previously defined carbonaceous chondrite groups, which comprise exclusively unequilibrated meteorites. However, since this initial definition a number of newly discovered meteorite finds have been classified as either CK3 or CK3-anomalous (Fig. 1b,c,d,h) (see Table 2a for sample names and references). All of these type 3 examples display many features typical of the CK group. In particular, they have high magnetite to metal ratios and fully equilibrated matrix olivines with compositions close to Fa_{31}. A type 3 designation for these samples is based on the preservation of generally well-developed zoning profiles in larger olivines located within chondrules and other coarse-grained objects (Fig. 1b,c,d). These are invariably zoned from Fa-rich exteriors to Fa-poor cores. However, from published descriptions (references in Table 2a) it would appear that, compared to the CVs, most CK3 chondrites are of a significantly higher metamorphic grade (see section 5.2.3).

4. RESULTS

4.1 Oxygen isotopes

The results of oxygen isotope analyses for all samples studied are given in Table 2a and plotted in terms of $\delta^{18}O$ versus $\delta^{17}O$ on Figs. 2, 3, and 4. The CCAM line (Clayton et al., 1977; Clayton and Mayeda, 1999), derived from analyses of mineral separates from calcium aluminium-rich inclusions (CAIs), is also shown for reference on each of these plots. Results for the CV chondrites are plotted on Fig. 2. In keeping with the results of previous studies (Clayton and Mayeda, 1999) the CV chondrites show a significant range in oxygen isotope compositions (approximately 6.5‰ with respect to $\delta^{18}O$). In comparison, CO chondrites, display relatively restricted compositional variation on a three-isotope diagram (Fig. 2)

(Greenwood and Franchi, 2004). Turning to the various CV subgroups, CV_R chondrites (Vigarano, Leoville, Efremovka and Arch) show more restricted variation than the oxidized CVs (Fig. 2). It is clear from Fig. 2 that the more phyllosilicate-rich CV_{oxB} chondrites tend to be lower in ^{16}O than the phyllosilicate-poor CV_{oxA} subgroup. This conclusion is consistent with the results of previous studies (Clayton and Mayeda, 1999). As is shown by the two sub-samples of ALH 84028 (Table 2a), which differ by nearly 2‰ with respect to $\delta^{18}O$, individual CV chondrites are fairly heterogeneous with respect to oxygen isotopes, a feature also seen in the study of Clayton and Mayeda (1999).

The oxygen isotope variation displayed by CK3s and related samples is shown in Fig. 3. These meteorites have oxygen isotope compositions very similar to the CVs, but with slightly greater scatter. This may reflect the influence of terrestrial weathering, as most members of this group are finds. The CK3s show almost no overlap with the phyllosilcate-rich CV_{oxB} chondrites (Fig. 3). Compared to CK3s, the equilibrated CKs (types 4 to 6) show slightly reduced levels of oxygen isotope variation, a feature which may reflect the influence of isotopic homogenization during thermal metamorphism. Based on their oxygen isotope compositions Clayton and Mayeda (1989, 1999) have suggested that the CK chondrites may be closely related to the CO group. This suggestion has been disputed by Kallemeyn et al. (1991) on the basis of textural differences between the relatively fine-grained COs and the much coarser grained CKs. Their oxygen isotope compositions (Fig. 3), also seem to indicate that these groups are not related. The CO chondrites form a tight cluster slightly displaced to the left of the CCAM (Clayton and Mayeda, 1999; Greenwood and Franchi, 2004), whereas the unequilibrated and equilibrated CKs generally plot closer to the CCAM line overlapping the CVs, to which they appear more closely related.

A number of the samples included in the present study have been analyzed previously. Analysis of reduced subgroup CVs by Clayton and Mayeda, (1999) show somewhat greater

variation than our results. In particular, Clayton and Mayeda (1999) report two analyses for Leoville which differ by 7‰. Clayton and Mayeda (1999) accounted for this variation in terms of the heterogeneous nature of CV chondrites, and in particular the presence of large CAIs which are relatively ^{16}O-rich compared to the bulk meteorite. Our analysis of Leoville has a composition intermediate to that of the two samples measured by Clayton and Mayeda (1999) and further illustrates the heterogeneous nature of these meteorites. For the oxidized CVs the coincidence between our analyses and those of Clayton and Mayeda (1999) is generally better than for the reduced CVs. The single exception to this is Bali, with Clayton and Mayeda (1999) again reporting two analyses that differ by 6‰. Our analysis of Bali has a composition slightly closer to the more ^{16}O-poor of the two Clayton and Mayeda (1999) analyses. Analyses of CK3s obtained in this study, with the notable exception of Watson 002, show reasonable agreement with previous results (Clayton and Mayeda, 1999; Zipfel et al., 2000; Ivanova et al., 2000; Greshake et al., 2003; Ivanova et al., 2003). The variable results for Watson 002, and to a lesser extent DAG 431 and SaU 085, indicate that, like the CVs, the CK3s are inherently heterogeneous meteorites.

The mean oxygen isotope composition for the equilibrated and unequilibrated CKs, and each of the three CV subgroups (CV_{oxA}, CV_{oxB}, CV_R) obtained in this study are compared with those from previous studies (Clayton and Mayeda, 1999; Ivanova et al., 2000; Zipfel et al., 2000; Greshake et al., 2003; Ivanova et al., 2003) in Table 2b and plotted on Fig. 4. There is good agreement between our data and that obtained in earlier studies for the equilibrated CKs and the two oxidized CV subgroups. There is somewhat poorer agreement for CK3s and the CV_R subgroup. The difference between our data and that of Clayton and Mayeda (1999) for CV_R subgroup is unsurprising in view of the heterogeneous composition of these meteorites. In particular, the two very distinct analyses of Leoville obtained in the study of Clayton and Mayeda (1999). The difference between our average CK3 value and that

calculated from data obtained in previous studies is predominantly a reflection of the variable analyses for Watson 002. The displacement of the CV_{oxB} subgroup towards ^{16}O-poor compositions, when compared to either CKs or other CV subgroups, is reproduced in both studies. This feature undoubtedly reflects the influence of aqueous alteration and is discussed further in section 5.2.8.

4.2. Magnetite analysis

Magnetite is the dominant opaque phase in both CK and CV_{oxA} and CV_{oxB} chondrites (Weisberg et al., 2006). Magnetite analyses from selected CV and CK chondrites are given in Table 3. Magnetites in the CK3 chondrite Watson 002 have slightly higher MgO (0.57±0.08 wt%), higher TiO_2 (0.95±0.07 wt%) and lower Cr_2O_3 contents (3.02±0.34 wt%) than the equilibrated CKs (DaG 250, DaG 275, Sleeper Camp 006) (MgO: 0.03-0.21 wt%, TiO_2: 0.22-0.51 wt%, Cr_2O_3: 3.56-4.98 wt%) (Table 3). Relatively high MgO and TiO_2 values in magnetites from Watson 002 (CK3) have also been reported by Geiger and Bischoff (1995). These authors point out that magnetites in Watson 002 lack the ubiquitous spinel ($MgAl_2O_4$) and ilmenite ($FeTiO_3$) lamellae found in equilibrated CKs and suggest that these relatively high MgO and TiO_2 values are a primary feature. In contrast, the lower MgO and TiO_2 values in equilibrated CKs probably reflect the more protracted cooling histories experienced by these meteorites (Geiger and Bischoff, 1995).

On Fig. 5 magnetites in CV and CK chondrites are plotted in terms of MgO v. Cr_2O_3. Magnetites in Allende (CV_{OxA}) define a relatively distinct field with MgO values generally less than Watson 002 but greater than Vigarano (CV_R). In terms of their Cr_2O_3 contents both Vigarano and Allende show considerable variation and at the high end overlap the values found in both unequilibrated and equilibrated CKs. Magnetites in Ningqiang (C3-ungrouped) tend to be relatively low in both MgO and Cr_2O_3. A plot of MgO v. Cr_2O_3 in magnetites has

previously been used as a means of discriminating between the CV and CK groups (Ivanova et al., 2003). However, the tightly constrained box (labeled 1 on Fig. 5) used by Ivanova et al. (2003) to characterize CV magnetites appears to have been based largely on the limited Allende dataset of Haggerty and McMahon (1979). If other CV magnetite data is taken into consideration (Rubin, 1991; Murakami and Ikeda, 1994; Simon et al., 1995) then this CV box expands dramatically (box labeled 2 on Fig. 5). It is clear from Fig. 5 that compositional variation in CV magnetites is considerable, and when the CK magnetite data from this study, and that of Geiger and Bischoff (1995), is taken into consideration (box 3, Fig. 5), there appears to be significant overlap between the two groups with respect to MgO v. Cr_2O_3.

However, in terms of their TiO_2 contents there appears to be a clear difference between magnetites in CV and CK chondrites. The TiO_2 content of magnetites in Watson 002 (0.95±0.07 wt%) is significantly greater than anything that has so far been measured in a CV chondrite (typically less than 0.1 wt%). If, as suggested by Geiger and Bischoff (1995), the composition of Watson 002 magnetites is indicative of primary values prior to subsolidus recrystallisation, then high TiO_2 contents may be an important characteristic feature of CK magnetites. Experimental evidence relevant to the formation conditions of magnetite with high primary TiO_2 contents (Geiger et al., 1989) is discussed further in section 5.2.1.

Literature data on magnetites in other groups of carbonaceous chondrites is relatively limited, but appears to indicate that these are compositionally distinct from those in CVs and CKs. Magnetites in CI, CM and CO chondrites are essentially pure Fe_3O_4 with elements such as Cr, Mg, Ni, Mn and Ti generally below detection limits (Lőhn and El Goresy 1992; Endress and Bischoff, 1993; Wlotzka et al., 1995; Shibata, 1996; Hua and Buseck, 1998). Only in the heavily metamorphosed CM2 chondrites B-7904 and Y-82162 (Ikeda, 1991; Kimura and Ikeda, 1992) are there magnetites with relatively high values of Cr_2O_3, NiO, MgO and Al_2O_3 similar to those we have measured in CVs and CKs. Although the oxygen

isotope composition of thermally heated CM2s is quite distinct from that of CVs and CKs (Clayton and Mayeda, 1999), and hence there is no genetic link between the groups, the compositional similarity of their magnetites suggests similar conditions of formation. Experimental work indicates that dehydrated CM2s, such as B-7904, were heated to temperatures between 700°C and 890°C (Nakoto et al., 2008). In comparison, Geiger and Bischoff (1991) estimated that CK chondrites experienced peak temperatures in the range 550 to 1000°C, whereas Neff and Righter (2006) give somewhat lower values of 277 to 653°C .

4.3 Bulk compositional results

When originally defining the CK group Kallemeyn et al. (1991) noted the very similar trends on Mg-normalized lithophile element abundance plots shown by CV and CK chondrites. However, despite these similarities Kallemeyn et al. (1991) emphasized various abundance ratio plots as a means of distinguishing between CVs and CKs, in particular Al/Mg v. Sc/Mg and Al/Mg v. Ca/Mg (Fig. 6a,b). In these diagrams the CK chondrites plot as a fairly distinct grouping, being well separated from CO chondrites, and relatively well separated from the CV chondrites. No CK3 chondrite samples had been identified at the time of the Kallemeyn et al. (1991) study. To examine whether these new samples support the view that CK chondrites form a distinct group we have analyzed the major and trace element compositions of a suite of CV and CK chondrites by ICP-MS. The results of this work are given in Table 4 and plotted on Fig. 7a,b,c.

At present the CK chondrite group contains only two falls, Karoonda and Kobe, the remaining 140 or so classified samples are finds which have experienced varying degrees of terrestrial weathering (Rubin and Huber, 2005; Huber et al, 2006). On a plot of Al/Mg v. Ca/Mg (Fig. 7a) the equilibrated CK chondrites NWA 1563 and Maralinga and the CK3s Camel Donga 003 and Watson 002 lie well away from the main group of samples. This most

likely reflects terrestrial weathering processes involving the loss of Mg and enrichment of Ca. A number of studies of hot desert ordinary chondrite finds have demonstrated that there is a systematic decrease in Mg (and Si) with increasing degrees of weathering (Gibson and Bogard 1978; Bland et al. 1998; Al-Kathiri et al. 2005). Increased levels of Ca in CKs from hot desert environments have been documented by Huber et al. (2006), which they ascribe to the formation of calcite-like weathering products. In the case Maralinga (CK4), the occurrence of carbonate veins, formed as result of terrestrial weathering processes, has been described by Keller et al. (1992). However, the CV_{oxB} chondrite fall Grosnaja also shows high values of Al/Mg and Ca/Mg compared to other CV and CK samples, and in this case this probably reflects the extensive and distinct asteroidal aqueous alteration assemblage seen in this meteorite (Keller and McKay, 1993). Once these samples have been excluded (Fig. 7b) it is evident that the clear separation between the CV and CK groups seen in the data of Kallemeyn et al. (1991) (Fig. 6a) is not reproduced in our new dataset. Rather than indicating that the CV and CK chondrites form distinct groups this plot suggests that both display broadly similar variation. On a plot of Al/Mg v. Sc/Mg (Fig. 7c), the CVs and CKs display overlapping variation (the very weathered sample Camel Donga 003 has been excluded from this diagram). The broader field defined by CKs on Fig. 7c is probably a reflection of the variable degrees of terrestrial alteration experienced by this group (Rubin and Huber, 2005; Huber et al., 2006).

The main implication of the new compositional data presented in this section is that Mg-normalized lithophile element abundance plots cannot be used as a simple tool to separate CV and CK chondrites. Instead it is clear that both groups show overlapping variation on such diagrams.

5. DISCUSSION

5.1 CV and CK chondrites: The significance of meteorite groups and clans

As pointed out by Weisberg et al. (2006) meteorite classification is a fundamental activity in cosmochemistry and provides the basic framework for any discussion of the origin and early evolution of the solar system. Classification necessarily involves assessing a range of evidence in an attempt to define similarities and differences between individual meteorites and groups of meteorites. It is an ongoing activity which requires continual reassessment as new samples are discovered and new lines of evidence emerge. Defining a meteorite group, in which all of the constituent members share common characteristics, is a fundamental part of this process. However, even where there is agreement on what members should be included, or excluded, from a group there are often clear differences of interpretation concerning the significance of the underlying interrelationships. Thus, in their review of the CV chondrites, Krot et al. (1995) stated " We assume that all CV chondrites came from a single asteroid". Young et al. (1999) went further and suggested that the mineralogy and oxygen isotope variation displayed by the CV, CM and CI groups could be explained in terms of fluid/rock interaction within a single carbonaceous chondrite parent body. In contrast, Bischoff (1998) suggested that many of the secondary alteration features displayed by carbonaceous chondrites formed either in the solar nebular, or in uncompacted protoplanetary objects that were destroyed prior to the final stage of parent body formation. Based on a study of chondrules in Kaba (CV_{oxB}) and the Allende-like portion of the Mokoia breccia, Kimura and Ikeda (1998) have also proposed that some secondary alteration of CV chondrites took place prior to the final parent body stage.

There is fairly general agreement that the CV and CK chondrites represent closely-related groups, such that Weisberg et al. (2006) have designated both as constituting a CK-CV clan. A good illustration of the relatively blurred demarcation between these groups is the

well-documented, multi-stage reclassification of the Ningqiang chondrite (Kallemeyn, 1996), which has variously been a CV, CV-an, CK-an and is currently classified C3-ungrouped by the Meteoritical Bulletin and CK3 by the Catalog of Meteorites. In fact Karoonda, from which the CK group takes its name, was classified as a CV chondrite by both Fitzgerald (1979) and McSween (1979). The overlap between the groups is also illustrated by the case of Sayh al Uhaymir 085 which, while being classified as a CV, displays characteristic features of the CK group, including the presence of large Cr-rich magnetite objects (Ivanova, et al., 2003). This lack of unambiguous classification criteria can also result in samples being left unassigned to either group. Thus, although Dar al Gani 055 has equilibrated matrix olivines with a composition of $Fa_{30.5\pm0.5}$ and various other features typical of the CK group (Weber et al., 1996), it was classified as C3-ungrouped.

In order to examine the nature of the relationship between CVs and CKs we look first at the various criteria used to classify the CKs. Our aim is to try and understand which of these may be primary i.e. nebular in origin, and which may be due to secondary processes i.e. parent body aqueous alteration and/or thermal metamorphism. One important feature in establishing separate groups for the CKs was the fact that all of the original members (excluding Ningqiang) were equilibrated (Kallemeyn et al., 1991). In view of the increasing number of new meteorites being classified as CK3s we attempt to identify whether the thermal regime experienced by this group was in fact distinct from that of the CVs. Our overall aim is to try and define with greater clarity the relationship between these groups. A subsidiary goal is to establish less ambiguous classification criteria for assigning samples to a particular group.

5.2 CK chondrites: Primary features or metamorphic overprint?

In their original definition Kallemeyn et al. (1991) proposed the following features as being characteristic of the CK group: (1) They are highly oxidized; (2) have low C contents; (3) very low contents of refractory inclusions; (4) an absence of coarse-grained rims around chondrules; (5) a high groundmass to chondrule ratio; (6) a chondrule size intermediate between the CO and CV groups; (7) refractory lithophile abundances intermediate between CO and CV groups; (8) an oxygen isotope composition plotting close to the CCAM line and overlapping the CO and CV groups; (9) equilibrated olivines with a composition close to Fa_{31}. However, most of these characteristic features are not primary in origin, but instead reflect a later metamorphic overprint. In this section we examine each of these characteristic features in turn in order to ascertain their origin and significance.

5.2.1 Oxidation state

Perhaps the most characteristic feature of CKs is their high oxidation state, such that the opaque mineral assemblage is dominated by the presence of magnetite (1.2 to 8.1 wt.%) with only trace to zero metal (Geiger and Bischoff, 1995; Neff and Righter, 2006). Neff and Righter (2006) point to the presence of variable metal in all CV subgroups as indicating that these formed under more reducing conditions than the CKs. However, some CV_{oxB} chondrites are also essentially devoid of metal and contain abundant phyllosilicates (McSween, 1977; Krot et al., 1995, 1998; Ohnishi and Tomeoka, 2002). Although the phyllosilicate-bearing CV_{oxB} assemblage would have formed at lower temperature (<300ºC) (Krot et al., 1998) than that recorded by the CK chondrites (section 4.2), the oxidation state of both may well have been similar during parent body reprocessing. The relatively high percentage of matrix material in both the CV_{oxB} subgroup and CKs may also indicate a genetic link between them (see section 5.2.5). Clearly, the oxidation state of CK chondrites, like the CV chondrites, is

far removed from that which prevailed in the solar nebula (Blum et al., 1989) and instead records post-accretionary conditions on the CK parent asteroid.

The highly oxidizing conditions that prevailed during the formation of the opaque assemblage in CKs have been studied by Geiger and Bischoff (1995). They point out that magnetite formation requires an oxygen fugacity at least as high as the wüstite-magnetite buffer, and the ubiquitous presence of Ni-rich olivines in these meteorites suggests conditions close to the Ni-NiO buffer. Heating experiments on Allende chips under controlled oxygen fugacity conditions (Ni-NiO buffer, 1050 and 1150°C for 4 days) (Geiger et al.,1989; Geiger and Bischoff, 1995) resulted in the formation of oxide phases with high concentrations of Ni, Mg, Ti, Cr and Al. The relatively high Ni content of the oxides formed in these experiments (1.9 wt‰ NiO) compared to the lower values found in CK magnetites (0.2-0.3 wt‰ NiO) (Table 3) is probably a reflection of the open system, non-equilibrium experimental conditions. Ni diffusion profiles were seen in the larger olivine grains and sulphur was completely lost from the system, so that none of the run products contained sulphides, which in CK chondrites can contain in excess of 40 wt% Ni (Geiger and Bischoff, 1995). Complete loss of S was also seen in the Allende heating experiments of Wulf et al. (1995) and it was noted by Matza and Lipschultz (1978) that discrete sulphides in heated Murchison do not survive above 1000°C. In contrast, peak metamorphic temperatures on the CK parent body probably did not exceed 1000 °C (Geiger and Bischoff, 1991; Neff and Righter, 2006) which, in contrast to the experiments, accounts for the ubiquitous presence of sulphides in these meteorites.

Despite the problems of simulating CK metamorphic conditions in the laboratory, the opaque assemblage produced in the experiments of Geiger and Bischoff (1995) is a reasonable match to that found in natural CK samples. These results support the possibility that CK chondrites could have formed during metamorphic heating of a CV-like precursor

under oxidizing conditions. The ilmenite and spinel exsolution lamellae developed in magnetites in equilibrated CKs would have formed during subsequent slow cooling.

5.2.2 Carbon content

Most members of the CK group are equilibrated and hence have low carbon contents. The CK4 fall Karoonda has a carbon abundance of 0.07 wt%, compared to 0.27 to 1.5 wt% in CVs (Pearson et al., 2006). No analyses are yet available for recently identified CK3 chondrites, however, the extensively weathered nature of these terrestrial finds (Huber et al., 2006) would severely limit the usefulness of such data when attempting comparisons with CV falls. This fact is clearly illustrated by the heavily altered CK4 find Maralinga which has carbon abundance of 0.28 wt% (Pearson et al., 2006). Antarctic CKs appear to have suffered less terrestrial contamination. Gibson and Yanai (1979) report a total carbon content for Yamato 693 (CK4/5) of 0.061 ± 0.004 wt%, while Pearson (2003) reports a value of 0.08±0.03 for the same sample. Values in the range 0.03-0.04 wt% are given by Jarosewich (2006) for the Antarctic CKs EET87526 (CK5), EET87860 (CK5/6), LEW87009 (CK6). Despite the limited data available for CKs it is clear that total carbon contents tend to decrease with increasing metamorphic grade, a feature also seen in both the ordinary (Hashizume and Sugiura, 1998) and CO chondrites (Greenwood and Franchi, 2004). As a defining characteristic of the CK group total carbon content is of limited value. The CK3s are all likely to be heavily contaminated and therefore cannot be usefully compared to CV falls, whereas the low carbon content of equilibriated CKs is merely a reflection of metamorphic grade.

5.2.3 Refractory inclusions

Kallemeyn et al. (1991) reported that CKs were characterized by a very low content of refractory inclusions, in marked contrast to all other groups of carbonaceous chondrites. Paradoxically they also noted that CKs had high refractory-lithophile abundances, intermediate between that of COs and CVs. The characteristics of the CK group proposed by Kallemeyn et al. (1991) were based almost exclusively on their studies of equilibrated samples and this may have led to a significant underestimate of the compliment of refractory inclusions within these meteorites. It is now well established that refractory inclusions in carbonaceous chondrites are highly susceptible to parent body alteration. In CO chondrites, for which a well-development metamorphic sequence has been established (Scott and Jones, 1990; Chizmadia et al., 2002), refractory inclusions show a clear sequence of changes in response to increasing degrees of thermal metamorphism (Greenwood et al., 1992; Russell et al., 1998). Melilite-bearing inclusions are abundant in CO3.0-3.4, rare in 3.5 and absent from types 3.6 to 3.8, where they are replaced by a fine-grained intergrowth of feldspathoids (metamorphic scale of Scott and Jones (1990), as modified by Chizmadia et al., (2002)). Spinel, which is close to end member $MgAl_2O_4$ in CO3.0, becomes increasing Fe-rich until grade 3.5, above which it takes on a relatively homogeneous hercynitic composition (50-60 mol% $FeAl_2O_4$). Perovskite ($CaTiO_3$) is replaced by ilmenite ($FeTiO_3$) in all types above grade 3.5.

Although as yet none of the meteorites classified as CK3 have been assigned a specific subgrade, on the basis of the limited published descriptions (Table 2a) it seems unlikely that any have experienced thermal metamorphic conditions significantly below those COs assigned a 3.5 grade. There is only one report of melilite in a CK3 CAI (Smith and Russell, 2003) and spinel when present is generally Fe-rich (Geiger et al., 1993; Ivanova et al., 2000). Given that CAIs would experience increasing degrees of recrystallisation with increasing

grade it is likely that only the more prominent inclusions will be identified during petrographic study. In fact a wide range of refractory inclusions have now been identified in CK chondrites, including: NWA 1559 (CK3) (Brandstätter et al., 2003), Watson 002 (CK3-an) (Geiger et al., 1993), Camel Donga 003 (CK3) (Met Bull 74) (Fig. 1h), DaG 431 (CK3-an) (Zipfel et al., 2000; Smith and Russell, 2003), Dhofar 015 (CK3) (Ivanova et al., 2000), Maralinga (CK4) (Keller, 1992; Keller et al., 1992; Kurat et al., 2002), Karoonda (CK4) (McPherson and Delaney, 1985; Greenwood et al., 2000a,b), NWA 1560 (CK4/5) (Bukovanská et al., 2003). A number of these descriptions suggest that refractory inclusions are relatively abundant in the meteorite being described. The high refractory-lithophile abundances in CKs, coupled with evidence from individual samples cited above, suggests that CKs contain relatively abundant, albeit often significantly altered, refractory inclusions.

5.2.4 Chondrule rims

As noted by Kallemeyn et al. (1991) CK chondrites tend to lack coarse-grained rims around chondrules, a feature which is well-developed in some CVs. However, as noted by Smith et al. (2003) in the case of DAG 431(CK3-an), this may be the result of metamorphic recrystallisation. Finer-grained rims around chondrules have been observed in DAG 431 (CK3-an) (Zipfel et al., 2000).

5.2.5 Matrix to chondrule ratio

CK chondrites typically have a high matrix content (Kallemeyn et al., 1991), with estimated values in the range 50 to 70% (Keller et al., 1992; Geiger et al., 1993; Zipfel et al., 2000; Smith and Russell 2003; Tomeoka et al., 2005). However, there are indications that lower matrix contents are present in some specimens (Pratesi et al., 2006). CKs have a significantly higher matrix content than either the CV_R or CV_{oxA} subgroups, which have

uniformly low contents in the range 35.9 to 38.4% (McSween, 1977). Higher matrix contents have been reported in three members of the CV_{oxB} subgroup Kaba, Grosnaja and Bali (McSween, 1977) with values in the range 50.0 to 51.3% and hence overlap with the those seen in CKs. Rubin et al. (1988) report that Ningqiang, which may be related to the CKs, has a matrix content of 50.5%. Matrix content is clearly not a criteria that can be used to discretely separate the CVs and CKs, rather it is more likely that a continuum exists, with meteorites such as Vigarano (34.5% matrix) (McSween, 1977) at one end and DAG 431 (70% matrix) (Zipfel et al., 2000) at the other .

5.2.6 Chondrule size distribution

In comparison with the CO and CM groups, CV and CK chondrites typically contain large chondrules (Weisberg et al., 2006). Reported size distributions in chondrules from CK chondrites fall within the range 150 to 2100μm (Geiger et al., 1993; Zipfel et al., 2000; Brandstätter et al., 2003; Bukovanská et al., 2003; Tomeoka et al., 2005). However, chondrules of up to 5mm diameter have been reported in the CK4 chondrite Maralinga (Keller et al., 1992). Reported average apparent chondrule diameters in CKs fall within the range 700 to 879 μm (Geiger et al., 1993; Tomeoka et al., 2005; Pratesi et al., 2006). While chondrules in CV chondrites show a very similar size distribution to that of CKs (McSween (1977) reports a range of 500 to 2000 μm), it has been suggested by Kallemeyn et al. (1991) that mean chondrule diameter in CVs is larger than in CKs i.e. ~1000 μm. However, more recent studies do not support this assertion and instead suggest that mean chondrule diameter in CVs show a similar range to CKs i.e. 655 to 850 μm (Paque and Cuzzi 1997; May et al., 1999). The evidence from chondrule size distribution data again highlights the similarities between the CVs and CKs.

5.2.7 Refractory lithophile abundances

In their original definition of the CK group Kallemeyn et al. (1991) placed particular weight on the evidence from refractory-lithophile abundance ratio plots, which appeared to show a distinction between CVs and CKs (see section 4.3). However, our new data, particularly for CK3 samples, does not support this conclusion and instead indicates that both CVs and CKs show overlapping variation, but with considerable scatter in the case of the CKs (Fig. 7a,b,c). This result is in keeping with the coarse-grained, heterogeneous character of both groups. As discussed earlier, refractory lithophile ratio plots do not offer a simple means of discriminating between CVs and CKs.

5.2.8 O-isotope composition

In terms of their average oxygen isotope values, the equilibrated and unequilibrated CKs and CV_R subgroup are essentially identical, with the CV_{oxA} subgroup showing only a slight displacement towards heavier values (Fig. 4). In contrast, the CV_{oxB} subgroup shows a significant displacement to isotopically heavier values (Fig. 4). CV_{oxB} chondrites contain phyllosilicates (Keller and Buseck, 1990; Keller et al., 1994), believed to be the products of parent body aqueous alteration (Krot et al., 1995, 1998). Magnetite and fayalite in the CV_{oxB} chondrites Kaba and Mokoia are also thought to have formed during secondary alteration and plot along the TFL close to the intersection with the CCAM line (Choi et al., 2000; Hua et al., 2005) (Fig.8). Hence, the displacement of CV_{oxB} chondrites to heavier isotopic values compared to the other CV subgroups is consistent with the evidence that they experienced more extensive aqueous alteration. In contrast, magnetites in Allende (CV_{oxA}) and Ningqiang (C3-ung) generally plot well below the TFL (Fig. 8), but have higher $\Delta^{17}O$ values than the associated silicates (Choi et al., 1997; Choi and Wasson, 2003; Hsu et al., 2006). This suggests that while magnetite in these meteorites was also formed during aqueous alteration,

water/rock ratios were considerably lower than in the CV_{oxB} chondrites. In the equilibrated CKs Karoonda (CK4) and Y-6903 (CK4) oxygen isotope analysis of plagioclase, olivine and magnetite separates are consistent with metamorphic equilibration at temperatures of 590ºC and 630ºC respectively (Clayton and Mayeda, 1999). While the majority of ion microprobe analyses of magnetites in equilibrated CKs (Greenwood et al., 2000a; Hiyagon et al., 2001) (Fig. 8) are broadly consistent with this mineral separate data, some magnetites in Karoonda CAIs appear to have reequilibrated on a very local scale, suggestive of very low water/rock ratios (Greenwood et al., 2000b). These studies indicate that CV_{oxA} and CKs both experienced aqueous alteration under similar conditions of very low water/rock ratios, in marked contrast to the higher ratios recorded by the CV_{oxB} chondrites.

The CK chondrites have high matrix contents (≥50%), when compared to the CV_R and CV_{oxA} subgroups, which have uniformly low values in the range 35.9 to 38.4% (McSween, 1977) (section 5.2.5). However, three members of the CV_{oxB} subgroup Kaba, Grosnaja and Bali (McSween, 1977) have values in the range 50.0 to 51.3% and hence show some overlap with the values seen in CKs. The essentially metal-free composition of both the CK group and CV_{oxB} subgroup indicates that both experienced a high oxidation state during alteration/metamorphism. On the basis of these similarities it might be tempting to suggest that a link exists between the CKs and CV_{oxB} subgroup, with the CKs being formed by metamorphism and dehydration of a Bali-like precursor material. However, this possibility can be ruled out by the oxygen isotope data. As demonstrated by the experiments of Mayeda and Clayton (1998), thermal dehydration of a phyllosilicate-bearing precursor rock will result in a significant heavy-isotope enrichment in the residual rock, with the precursor and residual rock both plotting on a single mass-dependent fractionation line. From this evidence it is clear that the CV_{oxB} subgroup cannot be parental to the CK group since it is shifted to heavier oxygen isotope values (Fig. 8), and the two groups do not lie on a single mass fractionation

line. The more likely possibility is that both had a common precursor, which then underwent relatively low temperature hydrous alteration in the case of the CV_{oxB} subgroup, and higher temperature thermal metamorphism in the case of the CKs. The lack of a marked heavy isotope shift in the CKs suggests that any water present must have been driven off before significant exchange could take place. The close match between the average oxygen isotope composition of relatively pristine CV_R subgroup and the CKs suggests that thermal metamorphism in the latter occurred under relatively dry conditions. The relatively ^{16}O-rich composition of magnetites in CK chondrites (Fig.8) also indicates that water/rock ratios were low during thermal metamorphism.

In summary, the oxygen isotope evidence indicates that both the CK and CV chondrites originated from a closely similar mix of nebular materials. Low petrographic grade CV_R chondrites are probably the closest in terms of their oxygen isotope composition to this CV-CK precursor material. It is interesting to note that, from an oxygen isotope perspective, the most significant difference is not between CV and CK chondrites, but rather between the CKs, CV_R and CV_{oxA} subgroups on the one hand and the CV_{oxB} subgroup on the other. This is a fundamental difference that cuts across the boundaries of the present classification framework.

5.2.9 Composition of olivines

Matrix olivines in all grades of CK chondrites (type 3 to 6) are equilibrated ($Fa_{31\pm3}$) and Ni-rich (NiO ~0.5 wt%) (Kallemeyn et al., 1991; Noguchi, 1993 Geiger and Bischoff, 1995). It is only olivines in macroscopic components within CK3s (chondrules, CAIs, large single crystal fragments) that display significant compositional variation,. Matrix olivines in CKs show many similarities to those in oxidized CVs (Brearley, 2009), however, the latter display much wider compositional variation (see section 3.1), and are invariably more Fe-rich

and Ni-poor (Weinbruch et al., 1990; 1994; Krot et al., 1995). These compositional difference may simply be a reflection of the lower metamorphic grade of CVs, even when compared to CK3s (see section 5.2.3). During closed system heating of Allende (CV_{oxA}), matrix olivines became progressively more forsteritic as run temperatures and heating times were increased (Geiger et al., 1989). In the highest temperature run, at the onset of partial melting (1200° C), the olivine composition was $Fa_{36.5}$ i.e. close to that of CK matrix olivines. Although the conditions in these experiments are far removed from those that would have prevailed in the CK chondrite parent body, they illustrate that full equilibration, between Fe-rich Allende matrix and its more Mg-rich macroscopic components, would result in formation of olivines with a composition close to that found in equilibrated CKs. Other heating experiments on Allende material demonstrate that, with increasing oxygen fugacity, Ni from decomposed Ni-rich metal becomes incorporated into newly formed FeO-rich olivine, which can contain up to 2.5 wt % Ni (Wulf et al., 1995).

It has been suggested that the ungrouped C4 chondrites Coolidge and Loongana 001 may also members of the CV-CK clan (Weisberg et al., 2006). However, these meteorites show a number of important differences in mineralogy when compared to either the CVs or CKs. Unlike the CKs and oxidized subgroup CVs, Coolidge and Loongana 001 do not contain magnetite, and although both of these meteorites are extensively weathered, they also contain relatively abundant Fe-Ni metal (Noguchi, 1994; Kallemeyn and Rubin, 1995). This might suggest an affinity with the CV_R subgroup (Noguchi, 1994). However, the composition of matrix olivines in these meteorites (~Fa_{11-13}) is significantly more Fe-poor that any of the CV subgroups (Krot et al., 1995) or the CKs (~Fa_{31}). Explaining the composition of matrix olivines in Coolidge and Loongana 001 by reequilibration of any known CV lithology is problematic. The most likely explanation for the origin of these meteorites is that they come from a distinct parent body to the CVs and CKs. However, further experimental work of the

type undertaken by Geiger et al. (1989) would help to clarify the relationships between these lithologies.

5.3 Revised classification criteria for CK chondrites

Based on the evidence discussed above and on the results of earlier studies (Kallemeyn et al., 1991; Noguchi, 1993 Geiger and Bischoff, 1995), we would suggest the following combination of features as a simple means of classifying CK chondrites: i) an oxygen isotope composition plotting below the TFL and close to the CCAM, ii) matrix olivines with a composition close to Fa_{31}, iii) a matrix content >50%, iv) abundant primary Ti-rich magnetites (as seen in type 3 samples by high TiO_2 contents (> 0.5 wt%), or in equilibrated samples by magnetites with well-developed ilmenite exsolution lamellae).

5.4 CK and CV chondrites: How many parent bodies?

As noted by Weisberg et al. (2006), there is a common assumption in meteorite taxonomy that all meteorites in the same group are from a common asteroidal parent body. In this section, we look at the nature and identity of the possible source asteroids for the CV and CK chondrites..

The mineralogical, geochemical and oxygen isotopic evidence presented in this paper appears to be compatible with three distinct scenarios for the asteroidal sources of the CV and CK chondrites (Fig. 9). It is possible that the CKs and each of the three CV subgroups are derived from distinct asteroids (Fig 9a). If this were the case mixed CV lithologies, as found in Vigarano, Mokoia and Leoville, would simply represent impact-related mixtures, perhaps derived from asteroids that formed in close proximity to each other (Jogo et al., 2008). However, the extent to which the various CV lithologies are intermixed appears to be more consistent with an origin on a single heterogeneously altered asteroid (Krot et al.,

2000). The present consensus view, with all of the CV subgroups being derived from a single source and the CK chondrites from a second distinct, thermally stratified parent body, is illustrated in Fig. 9b. A third possibility,, based on the evidence presented in this paper showing that CKs and CV share many common characteristics, is that both groups are derived from a single parent body (Fig. 9c). As discussed previously (section 5.2.3), there is clear evidence that CVs are somewhat lower grade in terms of thermal metamorphism than the CK3s. Studies of induced thermoluminescence indicate that, at least in terms of their silicate and oxide constituents, CVs are of relatively low petrographic grade, ranging from 3.0 to 3.3 (Guimon et al., 1995), whereas comparison with the CO metamorphic sequence (Scott and Jones, 1990; Chizmadia et al., 2002) indicates that most CK3s are grade 3.5 and above. It therefore remains entirely possible that both the CK and CV group are derived from a single thermally stratified parent body analogous to that which has been postulated for the ordinary chondrites (Wood, 2003; Trieloff et al., 2003). One argument against such a single source for the CKs and CVs is the lack of any evidence of CK-like material within CV regolith breccias. However, lack of such CK-like clasts might simply be because, prior to catastrophic disruption of this common parent body, impact and regolith gardening processes took place at too shallow a level to excavate CK-related material.

One means of examining whether CVs and CKs could have come from a common parent body is to look at their cosmic-ray exposure age distributions (Scherer and Schultz, 2000). The exposure ages of CV and CK chondrites show comparable patterns, with two clusters developed at ~9 and ~29 Ma (Scherer and Schultz, 2000). In comparison, CO chondrite exposure ages extend to higher values than either the CVs and CKs, whereas CI and CM chondrites are much lower, being generally less than 7 Ma (Scherer and Schultz, 2000). Scherer and Schultz (2000) suggest that the similarity in their cosmic-ray exposure age distributions supports a close relationship between CV and CK chondrites.

If the CV and CK chondrites were derived from a single large parent body (diameter ≥ 100km) that underwent catastrophic disruption then, in common with other such events (Fujiwara 1982; Bottke et al., 2001), it should have resulted in the formation of an identifiable asteroid family. It was first suggested by Bell (1988), on the basis of similar infrared and visible reflectance spectra, that members of the Eos asteroid family were a close match for CV and CO chondrites. Such asteroids were termed K class by Bell (1988). A recent study suggests that a better match for the Eos family is either the CK or R chondrites (Mothé-Diniz et al., 2008). Located in the outer asteroid belt at between 2.95 to 3.13 AU (Vokrouhlický et al. 2006; Mothé-Diniz et al., 2008), in a region dominated by C class asteroids (Gradie and Tedesco, 1982), it could be argued that CK chondrites are a more likely match to the Eos family than the R chondrites. The analysis of Mothé-Diniz et al. (2008) indicates that not all members of the Eos family can be matched to CK or R chondrites and that CV chondrites provide a suitable fit in some cases. It is therefore possible that the Eos family was formed by the disruption of a single CV-CK parent body with a structure similar to that shown in Fig. 9c.

The Eos family is estimated to contain 4400 members with an average diameter of ~31km, the largest fragment being Eos with a diameter of ~104 km diameter (Mothé-Diniz et al., 2008). The collisional event that formed the Eos family is estimated to have taken place 1,300 Ma ago (Vokrouhlický et al. 2006), with the original parent body having a diameter of approximately 218 km (Tanaga et al., 1999). However, whether or not the Eos family is composed of CV and CK chondritic material, it is important not to overstate our level of understanding concerning the sources of CK and CK chondrites. K class asteroids are present throughout the asteroid belt, so it is entirely possible that the CV chondrites are derived from multiple parent bodies (Burbine et al. 2001) and by implication the CK chondrites as well.

5.5 CK and CV chondrites: How many groups?

. In the preceding sections it has been shown that, not only do the CV and CK groups show similar petrologic and geochemical characteristics, but also that studies of their reflectance spectra and cosmic-ray exposure age distributions are consistent with a common asteroidal source for both groups. In the light of this evidence we now examine whether the current division of CV and CK chondrites into two distinct groups remains viable. Looking first at the CV chondrite group, this currently contains a diverse range of meteorites. It could therefore be argued that the present subgroup nomenclature should be abandoned and the CV chondrites divided into three distinct groups. However, such a proposal runs contrary to the evidence that individual meteorite samples often contain more than one type of CV lithology (McSween, 1977; Krot et al., 1998, 2000; Jogo et al., 2008). In itself this is not *prima facie* evidence of a genetic relationship between these various lithologies. In particular, the presence of solar wind gases shows that a number of CVs are best viewed as regolith breccias (Krot et al., 1995). However, all CVs show common characteristics, such as the presence of large chondrules and CAIs (Van Schmus, 1969), relatively coarse-grained matrices predominantly composed of Fe-rich olivine (Brearley and Jones, 1998), an oxygen isotope composition below the TFL and plotting close to the CCAM line (section 3.1.). It is therefore reasonable to regard the CVs as forming a single group. However, as discussed in section 5.1 and 5.2, most of the characteristic features of the CV group are also shared by the CKs. Recognition of these similarities has led to the establishment of a CV-CK clan (Weisberg et al., 2006). However, in view of their very close affinity it could be argued that a stronger taxonomic framework is now required to replace the loose nomenclature of a CK-CV clan (Weisberg et al., 2006). One approach would be to merge CV and CK chondrites into a single group. This could retain the overall "CV" designation, with the subgroup nomenclature providing a means for further subdivision. In such a scheme CK samples would be

reassigned to a new oxidized subgroup i.e. CV_{oxK}. Thus, unequilibrated CK chondrites such as Watson 002, or Camel Donga 003 would become $CV_{oxK,}$ whereas equilibrated samples would be $CV4\text{-}6_{oxK}$.

Objections to a single merged CV-CK chondrite group are: i) that so far no CK-like material has been found within CV regolith breccias and hence there is no evidence that both groups came from a single asteroidal source, and ii) the present two group classification system has gained wide and fairly general acceptance. As discussed in section 5.3, one possible explanation for the lack of CK material within CV regolith breccias is that the impact-related processing did not excavate material from sufficient depth on the CV-CK asteroid. In terms of gaining widespread acceptance any new proposal needs to be both workable and a better fit to the available scientific evidence than previous schemes. The evidence we have outlined in this paper leads us to believe that the CV and CK groups should more logically be combined into one single group. However, we recognize that this proposal may need to be tested further. In particular, additional detailed studies are required to establish a precise metamorphic scale within the CK3 chondrites.

6. CONCLUSIONS

In this paper we have examined in detail the relationship between the CV and CK chondrites. We have demonstrated that on the basis of a wide range of evidence both groups are closely related, particularly the CKs and the oxidized CVs. We have assessed the criteria used to delineate the CKs as a distinct group and find that in most cases these are secondary features resulting from metamorphic overprint. The CK and CV_{oxB} subgroup may both have formed from similar precursor material, prior to the onset of thermal metamorphism in the former and extensive aqueous alteration in the latter. Supporting evidence for both the CK and CV chondrites coming from a single common source is provided by their similar cosmic-

ray exposure age distributions. Recent reflectance spectral analysis is consistent with the CKs and CVs being derived from Eos family asteroids, which are believed to have formed as the result of the collisional breakup of a single large asteroid. It is therefore a distinct possibility that both groups were derived from a common thermally stratified parent body analogous to the postulated source for the ordinary chondrites. In view of the close affinity between the CV and CKs we would suggest that the present classification scheme is modified, with both of the existing two groups integrated to form a single group. While we suggest one possible scheme to achieve this, by including the CK chondrites as a subgroup of an expanded CV group, we recognize that further study of CK3 samples may be required to fully substantiate this proposal.

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TABLES

TABLE 1 Comparison of major and trace element abundances obtained by ICP-MS for Allende (CV) compared to a compilation of literature values

	Unit	D1	D1*	D2	D3	D3*	D4	D5	D6	D6*	Aver.	± 1σ	Lit.	± 1σ
Na	mg/g	3.53	3.43	3.71	3.82	3.84	3.48	3.44	3.51	3.48	3.58	0.16	3.48	0.23
Mg	mg/g	145	145	147	149	147	143	140	142	142	144	3	146	7
Al	mg/g	16.8	17	17	17.4	18.4	16.1	16.1	16.3	16.3	16.8	0.7	17.4	1.4
Ca	mg/g	17.7	17.9	17.9	17.3	17.3	18.8	19.9	18.8	20	18.4	1.0	18.0	1.1
Sc	µg/g	9.89	10.1	11.2	11.2	11.2	n.a.	n.a.	n.a.	n.a.	10.7	0.6	11.3	0.8
Ti	µg/g	705	707	734	804	801	n.a.	n.a.	n.a.	n.a.	750	49	920	45
V	µg/g	88	89.3	91	95	94.1	n.a.	n.a.	n.a.	n.a.	91	3	95	10
Cr	µg/g	3661	3665	3770	3418	3377	3525	3557	3569	3562	3567	122	3640	116
Mn	µg/g	1478	1483	1502	1519	1489	1382	1369	1380	1383	1443	62	1480	90
Fe	mg/g	240	234	238	234	230	213	211	213	214	225	12	237	9
Co	µg/g	758	747	769	743	742	680	675	685	689	721	38	644	47
Ni	mg/g	15.5	15	15.6	15.8	15.5	15.8	15.8	16.1	16.1	15.7	0.3	14.5	0.8
Cu	µg/g	119	117	121	128	125	108	107	109	108	116	8	115	15
Zn	µg/g	97.6	98.4	95.2	82.3	79.6	79.5	80.9	73.2	73.3	84.4	10.0	113.0	10.0
Ga	µg/g	5.71	5.86	6.75	5.88	5.97	4.88	5.33	5.51	5.24	5.68	0.53	6.02	0.52
Sr	µg/g	14.1	13.9	14.1	18.8	17.2	n.a.	n.a.	n.a.	n.a.	15.6	2.3	14.0	1.6

.D1 to D6 represent 6 different dissolutions of Allende powder (5-20mg) undertaken at the Open University. Replicates indicated by asterisk. All analyses were performed using an HP7500a Literature (Lit.) value for Allende see Bland et al. (2005) and references there in.

TABLE 2a. Oxygen isotope compositions of CV and CK chondrites.

	N	subgr.	$\delta^{17}O$‰	1σ	$\delta^{18}O$‰	1σ	$\Delta^{17}O$‰	1σ	Reference
CK3 AND RELATED CHONDRITES									
Camel Donga 003	2	CK3	-3.97	0.01	0.12	0.13	-4.03	0.06	1
DAG 431	2	CK3-an	-2.53	0.41	1.28	0.63	-3.20	0.08	2,3
Dhofar 015	4	CK3	-5.91	0.10	-2.24	0.16	-4.75	0.02	4
NWA 1559	1	CK3	-2.98		0.07		-3.01		5
NWA 1665	2	CK3-an	-5.38	0.07	-1.84	0.06	-4.43	0.04	6
Watson 002	2	CK3-an	-3.42	0.08	0.26	0.19	-3.56	0.01	7
DAG 055	2	C3-ung	-4.71	0.29	-1.04	0.39	-4.17	0.09	8
DAG 430	2	C3-ung	-5.30	0.08	-1.49	0.04	-4.53	0.06	9
Ningqiang	2	C3-ung	-4.66	0.27	-0.73	0.21	-4.28	0.16	10
SaU 085	2	CV	-2.81	0.18	1.76	0.24	-3.73	0.05	11
AVERAGE			**-4.17**	**1.20**	**-0.39**	**1.32**	**-3.97**	**0.58**	
CK (EQUILIBRATED)									
DAG 250	2	CK4/5	-4.51	0.03	-0.32	0.04	-4.35	0.00	12
DAG 275	2	CK4/5	-4.42	0.01	-0.47	0.11	-4.17	0.04	12
DAG 412	2	CK5	-4.26	0.06	-0.06	0.08	-4.23	0.02	13
DAG 1030	4	CK4/5	-3.99	0.17	0.39	0.24	-4.19	0.09	14
HaH 337	1	CK4	-3.69		-0.37		-3.50		15,16
Karoonda	2	CK4	-5.09	0.09	-1.02	0.17	-4.55	0.00	17
Maralinga	2	CK4	-4.75	0.06	-0.36	0.14	-4.56	0.01	18
NWA 1558	2	CK5/6	-4.15	0.10	0.05	0.24	-4.18	0.02	19
NWA 1560	2	CK4/5	-5.23	0.04	-1.18	0.03	-4.61	0.03	20
NWA 1905	2	CK5	-3.22	0.01	1.56	0.01	-4.03	0.02	14
AVERAGE			**-4.33**	**0.61**	**-0.18**	**0.77**	**-4.24**	**0.33**	
CV CHONDRITES OXIDISED (OxA subgroup)									
ALH84028,92	2	CV_{OxA}	-5.81	0.20	-1.67	0.18	-4.94	0.11	21,22
ALH84028	2	CV_{OxA}	-3.69	0.39	0.28	0.56	-3.84	0.09	21,22
Allende	4	CV_{OxA}	-3.00	0.10	1.20	0.22	-3.62	0.06	22,23,24
Axtell	4	CV_{OxA}	-1.85	0.52	2.29	0.48	-3.04	0.30	22,23,24
AVERAGE			**-3.59**	**1.67**	**0.53**	**1.68**	**-3.86**	**0.79**	
CV CHONDRITES OXIDISED (OxB subgroup)									
Bali	4	CV_{OxB}	-2.21	0.41	2.10	0.49	-3.30	0.17	22,23,24
Grosnaja	4	CV_{OxB}	-1.77	0.43	2.95	0.60	-3.31	0.14	22,23,24
Kaba	4	CV_{OxB}	-2.62	0.59	1.56	0.60	-3.43	0.31	22,23,24
Mokoia	2	CV_{OxB}	-1.85	0.28	2.56	0.40	-3.18	0.07	22,23,24
AVERAGE			**-2.11**	**0.39**	**2.29**	**0.60**	**-3.31**	**0.10**	
CV CHONDRITES OXIDISED (ungrouped)									
ALHA81003,25	1	$CV_{Oxungr.}$	-3.09		1.80		-4.03		22,25
ALH85006	2	$CV_{Oxungr.}$	-3.82	0.30	0.17	0.40	-3.91	0.10	21,22
CV CHONDRITES REDUCED									
Vigarano	3	CV_R	-4.20	0.07	0.11	0.17	-4.25	0.03	23
Leoville	3	CV_R	-5.03	0.35	-0.66	0.38	-4.69	0.17	23
Efremovka	2	CV_R	-4.15	0.25	-0.24	0.30	-4.03	0.10	23
Arch	2	CV_R	-3.40	0.11	1.09	0.09	-3.96	0.06	23
AVERAGE			**-4.19**	**0.67**	**0.07**	**0.75**	**-4.23**	**0.33**	
CV CHONDRITES UNGROUPED									
GRO95652	2	$CV_{ungr.}$	-6.91	1.84	-3.42	1.89	-5.14	0.86	12

N = number of replicates. References: [1] Met. Bull. 74, 1993, [2] Zipfel et al., 2000; [3] Smith and Russell 2003, [4] Ivanova et al., 2000, [5] Brandstätter et al., 2003, [6] Greshake et al., 2003, [7] Geiger et al., 1993, [8] Weber et al., 1996, [9] Met. Bull. 83, 1999, [10] Rubin et al, 1988, [11] Ivanova et al., 2003, [12] Met. Bull. 82, 1998, [13] Met. Bull 84, 2000, [14] Met. Bull. 88, 2004, [15] Pratesi et al., 2006; [16] Met. Bull. 90, 2006 , [17] Fitzgerald 1979, [18] Keller et al., 1992, [19] Met. Bull. 87, 2003, [20] Bukovanská et al., 2003, [21] Met. Bull. 76, 1994; [22] Krot et al., 1998, [23] McSween 1977, [24] Krot et al., 1995, [25] Kallemeyn 1987

TABLE 2b Average isotopic composition of CV and CK chondrites

	N*	$\delta^{17}O$‰	1σ	$\delta^{18}O$‰	1σ	$\Delta^{17}O$‰	1σ
CK3 (this study)	10	-4.17	1.20	-0.39	1.32	-3.97	0.58
Previous CK3	7	-3.43	2.07	1.08	2.85	-3.99	0.61
CK4-6 (this study)	10	-4.33	0.61	-0.18	0.77	-4.24	0.33
Previous CK4-6	13	-4.61	0.45	-0.73	0.62	-4.23	0.27
CV_{oxA} (this study)	4	-3.59	1.67	0.53	1.68	-3.86	0.79
Previous CV_{oxA}	3	-3.74	1.90	0.22	2.24	-3.86	0.74
CV_{oxB} (this study)	4	-2.11	0.39	2.29	0.60	-3.31	0.10
Previous CV_{oxB}	4	-2.06	2.12	2.48	2.25	-3.35	0.95
CV_R (this study)	4	-4.19	0.67	0.07	0.75	-4.23	0.33
Previous CV_R	5	-5.52	2.26	-1.33	2.83	-4.83	0.81

N=number of individual meteorite samples
See text for references

	Allende N=31		Sleeper Camp 006 N=10		DaG 275 N=52		Vigarano N=31		DaG 250 N=64		Watson 002 N=40		Ningqiang N=7	
	Average	± 1σ	Average	± 1σ	Average	± 1σ	Average	± 1σ	Average	± 1σ	Average	± 1σ	Average	± 1σ
MgO	0.31	0.17	***(0.03)***	0.04	0.21	0.06	***(0.03)***	0.02	0.07	0.08	0.57	0.08	0.17	0.06
Al2O3	1.32	0.73	0.63	0.44	1.93	0.30	0.12	0.10	1.09	0.61	2.95	0.17	1.30	0.09
SiO2	0.10	0.06	0.08	0.09	***(0.06)***	0.03	0.08	0.03	***(0.05)***	0.05	0.21	0.21	0.10	0.03
CaO	0.23	0.34	0.42	0.48	0.34	0.53	0.14	0.16	0.12	0.31	0.60	0.56	0.37	0.34
TiO2	0.06	0.03	0.22	0.17	0.51	0.80	***(0.02)***	0.01	0.31	0.28	0.95	0.07	0.17	0.09
V2O3	***(0.03)***	0.02	0.11	0.02	0.13	0.02	***(0.02)***	0.01	0.11	0.02	0.14	0.02	0.06	0.03
Cr2O3	2.26	0.93	3.56	0.13	4.98	0.23	1.92	0.86	3.97	0.19	3.02	0.34	1.17	0.62
MnO	**(0.02)**	0.02	0.04	0.02	0.06	0.02	***(0.02***)	0.02	0.04	0.02	0.09	0.02	***(0.03)***	0.01
FeO	88.72	1.58	88.62	1.51	84.64	1.54	90.37	1.01	87.05	1.02	84.60	1.23	88.76	1.04
Fe oxide*	95.23	1.71	95.10	1.60	90.71	1.65	97.03	1.10	93.35	1.10	90.74	1.28	95.63	0.97
Fe2O3*	65.01	1.42	64.61	0.95	60.57	1.27	66.47	0.97	62.85	0.92	61.30	0.52	68.63	1.39
FeO*	30.22	0.72	30.49	0.73	30.14	0.76	30.56	0.29	30.50	0.44	29.43	0.89	27.00	2.00
CoO	0.07	0.02	0.08	0.02	0.07	0.02	0.07	0.02	0.06	0.02	0.07	0.02	nd	nd
NiO	0.18	0.15	0.20	0.03	0.22	0.04	***(0.07)***	0.05	0.26	0.04	0.33	0.03	0.25	0.34
Total	93.32	0.67	93.98	0.56	93.16	0.63	92.86	0.48	93.16	0.58	93.53	0.69	92.40	0.42
Total*	**99.83**	**0.68**	**100.45**	**0.63**	**99.22**	**0.67**	**99.52**	**0.52**	**99.45**	**0.60**	**99.67**	**0.72**	**99.27**	**0.48**

Table 3 Magnetite analyses by WDS electron microprobe, expressed as wt% element oxides. Data processed initially with stoichiometric oxygen assigned to Fe as Fe^{2+} (i.e. as FeO), hence shortfall in analysis Totals. Fe^{3+} then calculated, based on the shortfall of trivalent ions after allocation of all other 3+, 4+ and 5+ ions to fill a hypothetical spinel B structural site (note that for ideal magnetite, the 'trivalent' total is 2 for 4 oxygen atoms, but trivalent iron actually occupies both A and B sites in the 'inverted' spinel structure). Fe_2O_3* and FeO* wt % then calculated from ratio of Fe^{3+} (determined in previous step) to Fe^{2+} (remaining Fe ions), finally all oxides summed to give Total* including extra oxygen for Fe^{3+}. Very similar values for Fe^{2+}, Fe^{3+}, Fe_2O_3, FeO* and Total* were also calculated from the total cation charge balance calculation for stoichiometric oxygen anions. Cobalt was not determined (nd) for Ningqiang. Element detection limits were calculated by convention as wt% equivalent to 3 times sigma for background count rate: Mg 0.02; Al 0.02; Si 0.04; Ca 0.02; Ti 0.02; V 0.02; Cr 0.03; Mn 0.03; Fe 0.03; Co 0.03; Ni 0.03. Those average values shown as bracketed and in bold italics (e.g. MgO in Vigarano) indicate that more than half of their constituent values fell below the detection limit for the individual element determination.

TABLE 4. Major, minor and trace element analyses of CV and CK chondrites

		Allende average	Bali	Grosnaja	Kaba	Vigarano	SAU085
		CVoxA	CVoxB	CVoxB	CVoxB	CV_R	CV
replicates		8.00				2.00	
23 Na	mg.g	3.60	4.63	3.47	3.28	2.83	2.56
24 Mg	mg.g	144.39	151.6	133.9	136.8	147.29	135.2
27 Al	mg.g	16.81	18.29	21.37	13.08	17.11	15.86
44 Ca	mg.g	18.46	17.28	22.57	13.73	18.11	16.68
45 Sc	ppm	10.86	11.10	10.93	9.55	11.07	12.23
47 Ti	ppm	760.95	715	883	568	750.66	837
51 V	ppm	92.04	94.0	97.2	73.3	90.77	88.4
53 Cr	ppm	3554.97	4142	3680	3625	3791.66	3780
55 Mn	ppm	1437.83	1529	1539	1549	1434.29	1271
57 Fe	mg.g	224.08	245.6	231.1	240.7	239.37	241.7
59 Co	ppm	717.73	687	728	718	736.69	566
62 Ni	ppm	15.77	15.15	13.79	16.71	14.47	13.15
63,65Cu	ppm	115.54	117		123	109.11	124
67 Zn	ppm	82.69	121	161	109	82.37	94
71 Ga	ppm	5.66	6.51	6.77	6.32	5.84	5.15
88 Sr	ppm	16.41	17.35	21.66	15.81	18.20	342.13
Atomic Ratio							
(Al/Mg)*100		10.49	10.87	14.38	8.62	10.46	10.56
(Ca/Mg)*100		7.75	6.91	10.23	6.09	7.46	7.48
(Sc/Mg)*10^5		4.07	3.96	4.41	3.77	4.06	4.89
Al/Mn		23.80	24.36	28.27	17.20	24.29	25.41
(Zn/Mn)*100		4.83	6.64	8.76	5.93	4.83	6.24

		Camel Donga 003	NWA1559-D2	DAG 431	Watson 002	Dhofar 015	DAG 430
		CK3	CK3	CK3-an	CK3-an	CK3	C3-ung
replicates							
23 Na	mg.g	0.34	2.66	3.43	2.79	1.71	2.80
24 Mg	mg.g	94.0	159.4	151.6	129.2	156.0	160.6
27 Al	mg.g	30.79	18.58	16.13	16.29	14.34	15.47
44 Ca	mg.g	28.46	20.05	17.04	46.51	16.15	17.76
45 Sc	ppm	26.90	12.94	11.72	11.51	12.65	11.73
47 Ti	ppm	1592	827	778	697	820	767
51 V	ppm	227.8	109.0	97.6	96.3	90.9	87.4
53 Cr	ppm	3192	3811	4024	3350	3767	3826
55 Mn	ppm	5416	1535	1484	1303	1271	1540
57 Fe	mg.g	256.6	238.4	241.2	228.2	244.9	232.7
59 Co	ppm	713	335	430	304	490	520
62 Ni	ppm	12.38	3.35	3.75	2.80	6.54	14.34
63,65Cu	ppm	95	107	110	83	70	100
67 Zn	ppm	296	122	54	73	69	74
71 Ga	ppm	11.70	5.51	4.46	5.33	3.34	5.34
88 Sr	ppm	55.43	117.76	18.14	40.64	37.55	26.70
Atomic Ratio							
(Al/Mg)*100		29.51	10.50	9.58	11.36	8.28	8.67
(Ca/Mg)*100		18.36	7.63	6.82	21.84	6.28	6.70
(Sc/Mg)*10^5		15.47	4.39	4.18	4.82	4.38	3.95
Al/Mn		11.57	24.64	22.13	25.45	22.97	20.45
(Zn/Mn)*100		4.60	6.66	3.08	4.71	4.54	4.03

TABLE 4 (continued)

		Ningqiang	Karoonda	Maralinga	DAG 250	DAG 275	NWA 1560	NWA 1563
		C3-ung	CK4	CK4	CK4/5	CK4/5	CK4/5	CK5
replicates				2.00		2.00		
23 Na	mg.g	3.96	4.88	3.62	3.39	3.13	2.51	4.76
24 Mg	mg.g	134.4	168.4	147.66	145.1	153.84	154.3	146.9
27 Al	mg.g	13.07	21.74	17.72	16.27	15.15	13.75	17.10
44 Ca	mg.g	15.27	19.46	28.12	18.00	16.05	18.80	34.13
45 Sc	ppm	9.12	11.22	10.20	11.77	12.33	11.73	9.95
47 Ti	ppm	635	666	692.56	761	777.84	757	726
51 V	ppm	80.2	81.7	87.16	98.2	96.16	96.4	95.5
53 Cr	ppm	3916	3639	3197.36	3931	3948.26	3521	3873
55 Mn	ppm	1332	1601	1692.35	1471	1495.48	1450	1566
57 Fe	mg.g	237.9	246.4	233.38	245.3	242.64	258.7	255.0
59 Co	ppm	669	586	416.67	689	440.45	446	301
62 Ni	ppm	13.48	11.60	5.07	16.28	3.70	5.09	2.86
63,65Cu	ppm	132		88.36	98	78.68	75	101
67 Zn	ppm	103	81	24.24	74	68.30	72	111
71 Ga	ppm	5.77	4.64	4.60	5.41	4.72	4.98	5.97
88 Sr	ppm	16.54	23.41	40.68	29.15	22.00	26.02	53.21
Atomic Ratio								
(Al/Mg)*100		8.76	11.63	10.81	10.10	8.87	8.03	10.49
(Ca/Mg)*100		6.89	7.01	11.55	7.53	6.33	7.39	14.09
(Sc/Mg)*10^5		3.67	3.60	3.73	4.39	4.33	4.11	3.66
Al/Mn		19.98	27.65	21.32	22.52	20.62	19.31	22.24
(Zn/Mn)*100		6.52	4.25	1.20	4.25	3.84	4.14	5.95

FIGURE CAPTIONS

Figure 1. (a) Coarse-grained type I porphyritic olivine chondrule from Allende (CV_{oxA}). At the margins, particularly along the right-hand side of the image, there is evidence of slight Fe diffusion from the matrix. (b) Coarse-grained type I porphyritic olivine chondrule in Camel Donga 003 (CK3). Compared to Allende chondrules (Fig 1a) the Fe-rich rims are wider, such that the more forsterite-rich areas are reduced to cores within the larger central grains. Matrix olivines, and those at the edge of the chondrules, are equilibrated with a composition of Fa_{34} . The edge of the chondrule is picked out by a thin layer of magnetite. (c) Watson 002 (CK3-an. A coarse-grained porphyritc chondrule in the upper right corner of the image shows the development of a wide Fe-rich rim where it is in contact with the surrounding matrix. Olivine in the matrix (mid-gray) is equilibrated with an average composition of Fa_{34-4} (Geiger et al., 1993). (d) Fragments of type I porphyritic olivine chondrules in Dar al Gani 055 (C3-ung). Olivine grains show evidence of considerable Fe-Mg exchange, with diffuse more forsteritic-rich areas present only in some grains. (e) Dar al Gani 275 (CK4/5) showing typical recrystallised and equilibrated CK texture. Bright objects are magnetite-rich, Fe-Mg silicates are mid-grey, dark areas are plagioclase rich. The magnetite-rich object to the right of the large chondrule (upper-left corner of image) is shown in detail in Fig. 1f. (f) Magnetite-rich object in Dar al Gani 275 (CK4/5). Magnetite (large bright grain) contains rounded inclusions of Cl-apatite (dark grey). Exsolution lamellae of ilmenite are developed along several crystallographic orientations (mid-grey). Sulphide-rich blebs (small bright grains) are also well developed. The magnetite grain is enclosed by a rim of plagioclase (dark grains). (g) Karoonda (CK4 fall) Type I porphyritic olivine chondrule with distinct magnetite-rich objects along the margin. Olivines in both matrix and chondrules (mid-grey) are fully equilibrated ($Fa_{31.2\pm0.6}$ Kallemeyn et al., 1991). Dark areas within the chondrule are plagioclase, bright areas are magnetite. (h) Altered CAI in Camel Donga 003 (CK3). Bright bands of hercynitic

spinel (h-s) alternate with fine-grained felspathoidal-rich areas (fel). By analogy with CAIs in CO3 chondrites the feldspathoidal-rich areas replace primary melilite and hence indicate that Camel Donga 003 is at least 3.5 in petrographic grade (metamorphic scale of Scott and Jones (1990), as modified by Chizmadia et al. (2002)).

Figure 2. Oxygen isotopic compositions of CV and CO3 chondrites. CCAM: carbonaceous chondrite anhydrous mineral line (Clayton et al., 1977; Clayton and Mayeda, 1999).

Figure 3. Oxygen isotopic composition of CK chondrites. Shaded areas for CO and CV chondrites from Fig.2. CCAM: carbonaceous chondrite anhydrous mineral line (Clayton et al., 1977; Clayton and Mayeda, 1999).

Figure 4. Average oxygen isotope compositions for CV and CK chondrites obtained in this study compared to previously published results (see text for references). All points are shown in relation to the CCAM line (Clayton et al., 1977 ;Clayton and Mayeda 1999).

Figure 5. MgO v. Cr_2O_3 (wt%) analyses for magnetites in CV and CK chondrites. Box labelled "1" from Ivanova et al., (2003). Box labelled "2" includes CV magnetite data of Haggerty and McMahon (1979); Rubin (1991); Murakami and Ikeda (1994); Simon et al. (1995). Box labelled "3" CK magnetite data Geiger and Bischoff (1995).

Figure 6a. Bulk refractory-lithophile abundance ratio plot of Kallemeyn et al. (1991).

Figure 6b. Bulk refractory-lithophile abundance ratio plot of Kallemeyn et al. (1991).

Figure 7a. Bulk refractory-lithophile abundance ratio plot. CV and CK chondrite data this study. CM, CI and CO chondrite data from Kallemeyn and Wasson (1981).

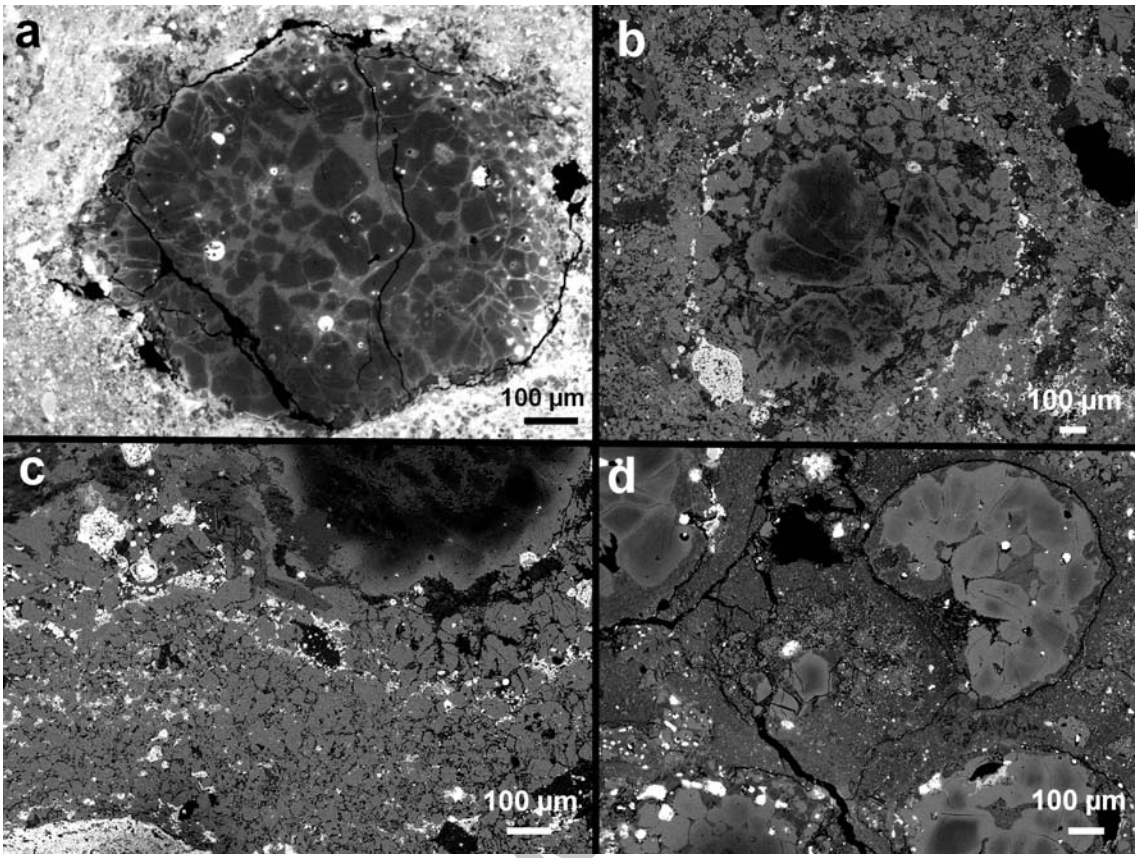
Figure 7b. Bulk refractory-lithophile abundance ratio plot. CV and CK chondrite data this study. CM2, CI and CO3 chondrite data from Kallemeyn and Wasson (1981).Sample abbreviations: Kar-Karoonda, DO15-Dhofar 015, V-Vigarano, K-Kaba, Al-Allende, B-Bali, Ni- Ningqiang

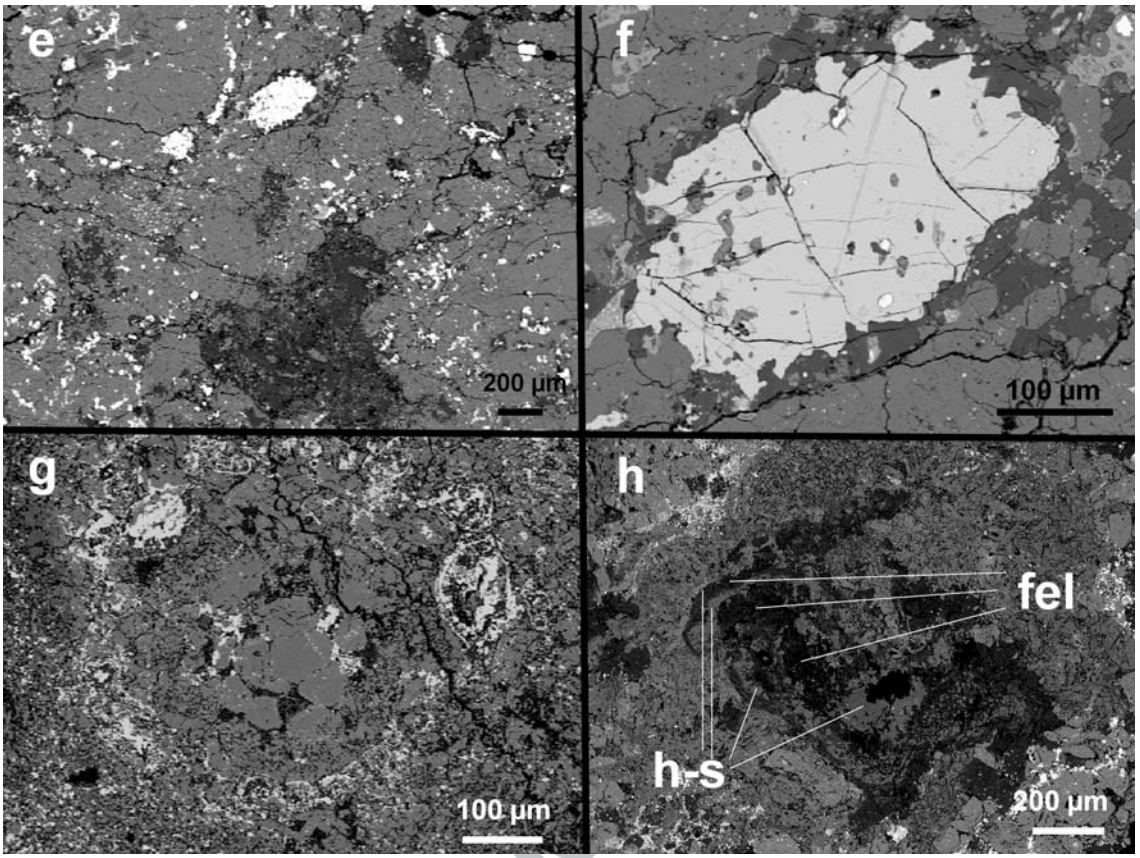
Figure 7c. Bulk refractory-lithophile abundance ratio plot. CV and CK chondrite data this study. CM2, CI and CO3 chondrite data from Kallemeyn and Wasson (1981).Sample abbreviations: Kar-Karoonda, DO15-Dhofar 015, V-Vigarano, K-Kaba, Al-Allende, B-Bali, Ni- Ningqiang, G-Grosnaja.

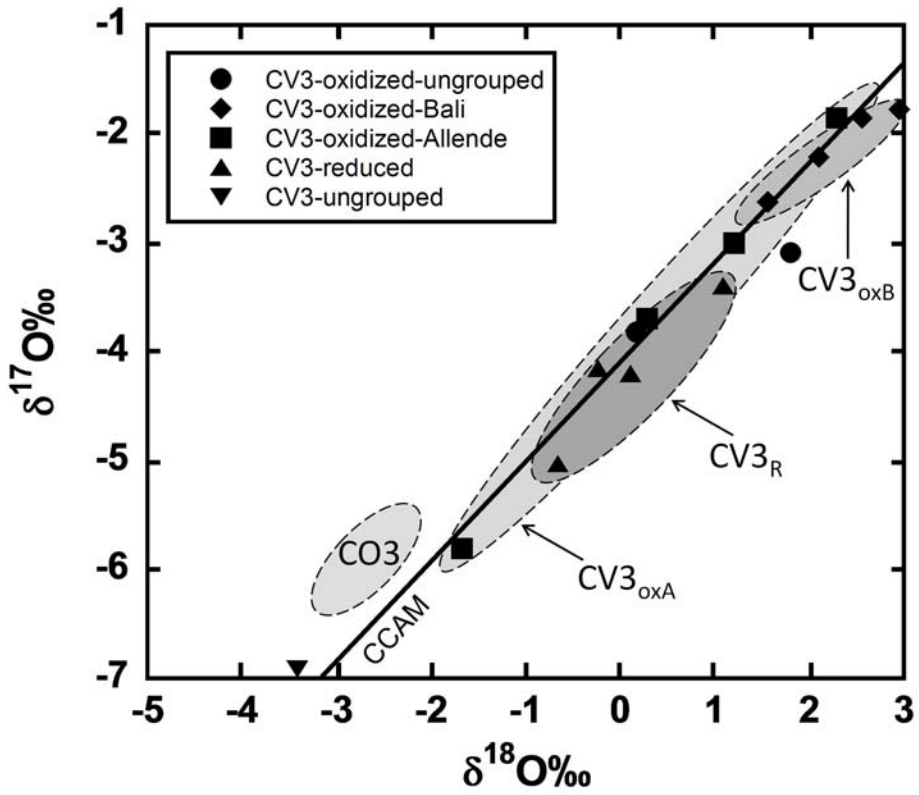
Figure 8. Oxygen three isotope plot for CV and CK chondrites. Squares: average analysis for each group from Table 2a. CCAM = carbonaceous chondrite anhydrous mineral line (Clayton et al., 1977; Clayton and Mayeda, 1999). TFL = Terrestrial Fractionation Line. Ion probe analyses: [1] Choi et al., 2000; [2] Hua et al., 2005; [3] Hiyagon et al., 2001; [4] Greenwood et al., 2000a; [5] Choi et al., 1997; [6] Choi and Wasson, 2003.

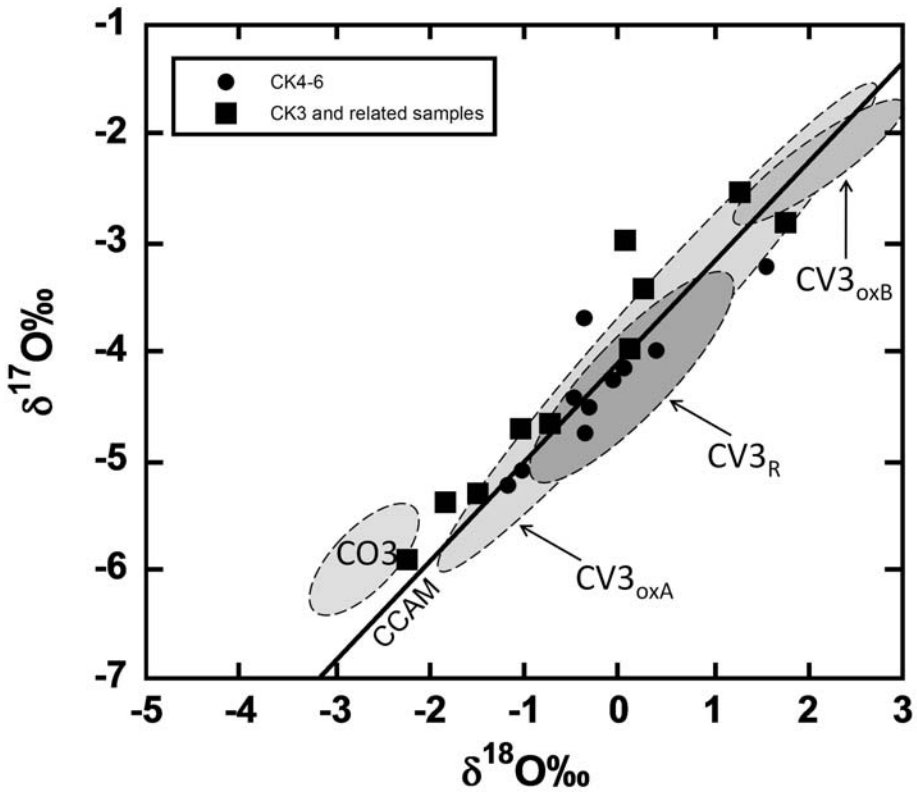
Figure 9. Schematic diagram showing alternative models for the source asteroids of CV and CK chondrites. (A): Each of the three CV subgroups have individual asteroidal sources and the CK chondrites are derived from a fourth, thermally stratified body. (B): All the CV3 subgroups are derived from a single heterogeneous source, with a well mixed outer layer of regolith. The CKs are derived from a distinct, thermally stratified asteroid. (C): The CVs and

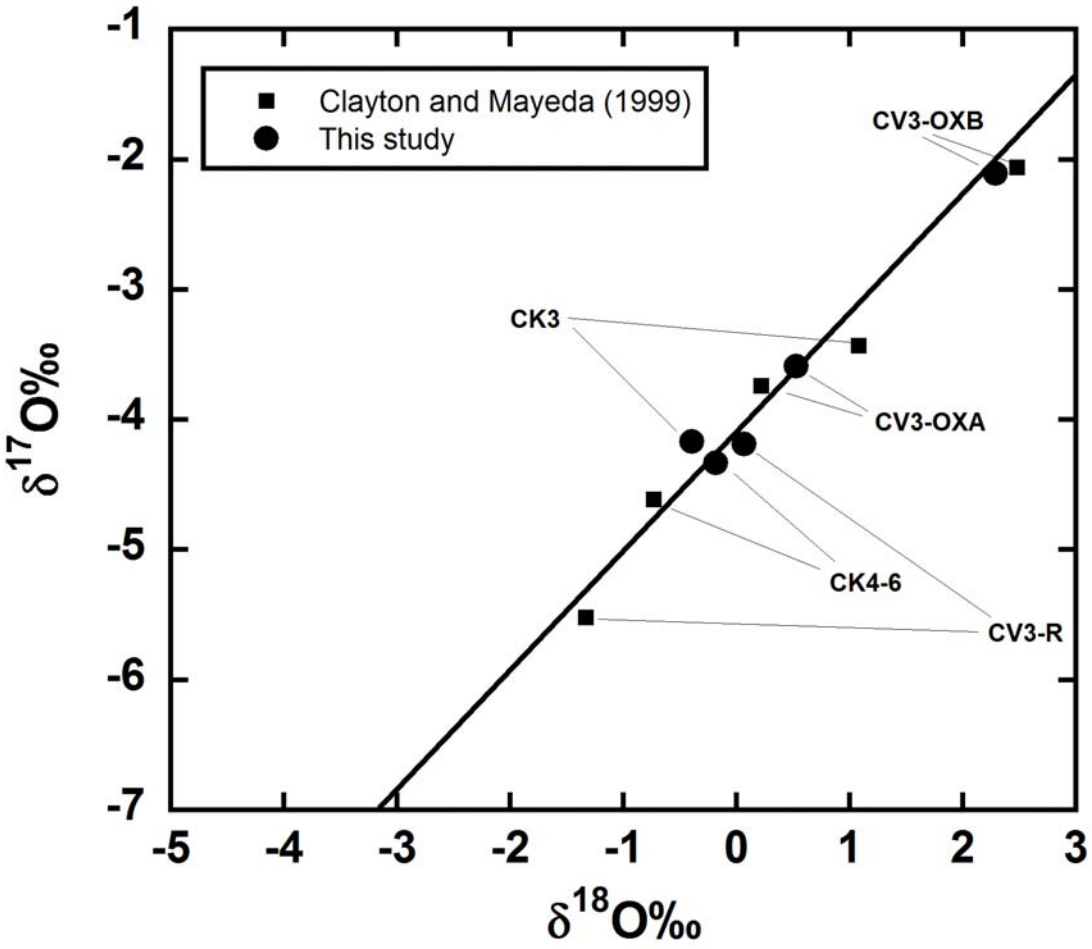
CKs are all derived from a single heterogeneous and thermally stratified source. The CKs form the central core with the lower grade CVs towards the exterior. The outer regolith breccias do not contain CK fragments because impact processes, prior to total disruption of the asteroid, did not penetrate to sufficient depth. One possibility for the source of the CK and CV chondrites is the parent asteroid that gave rise to the Eos family of asteroids (see text for further discussion).

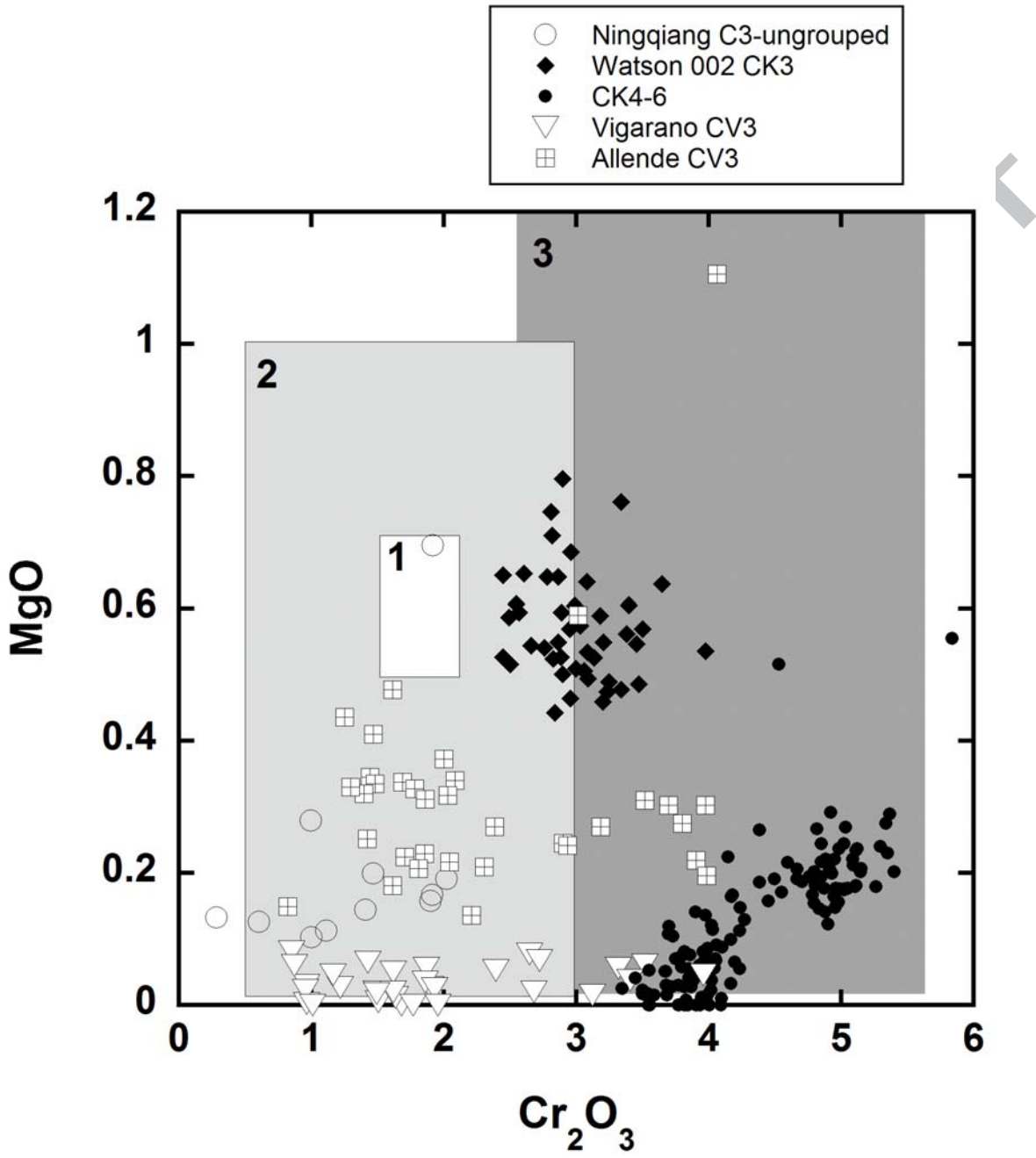


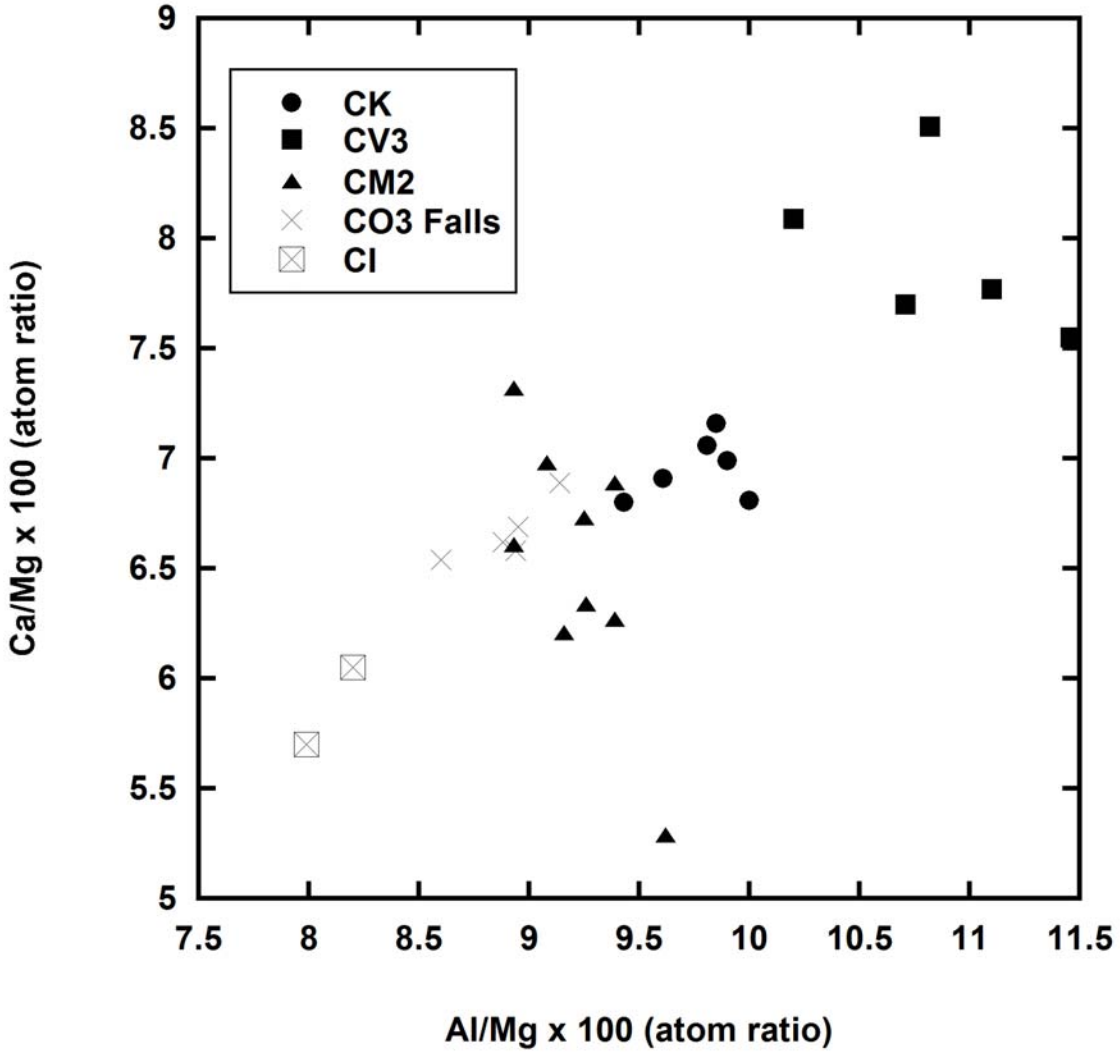


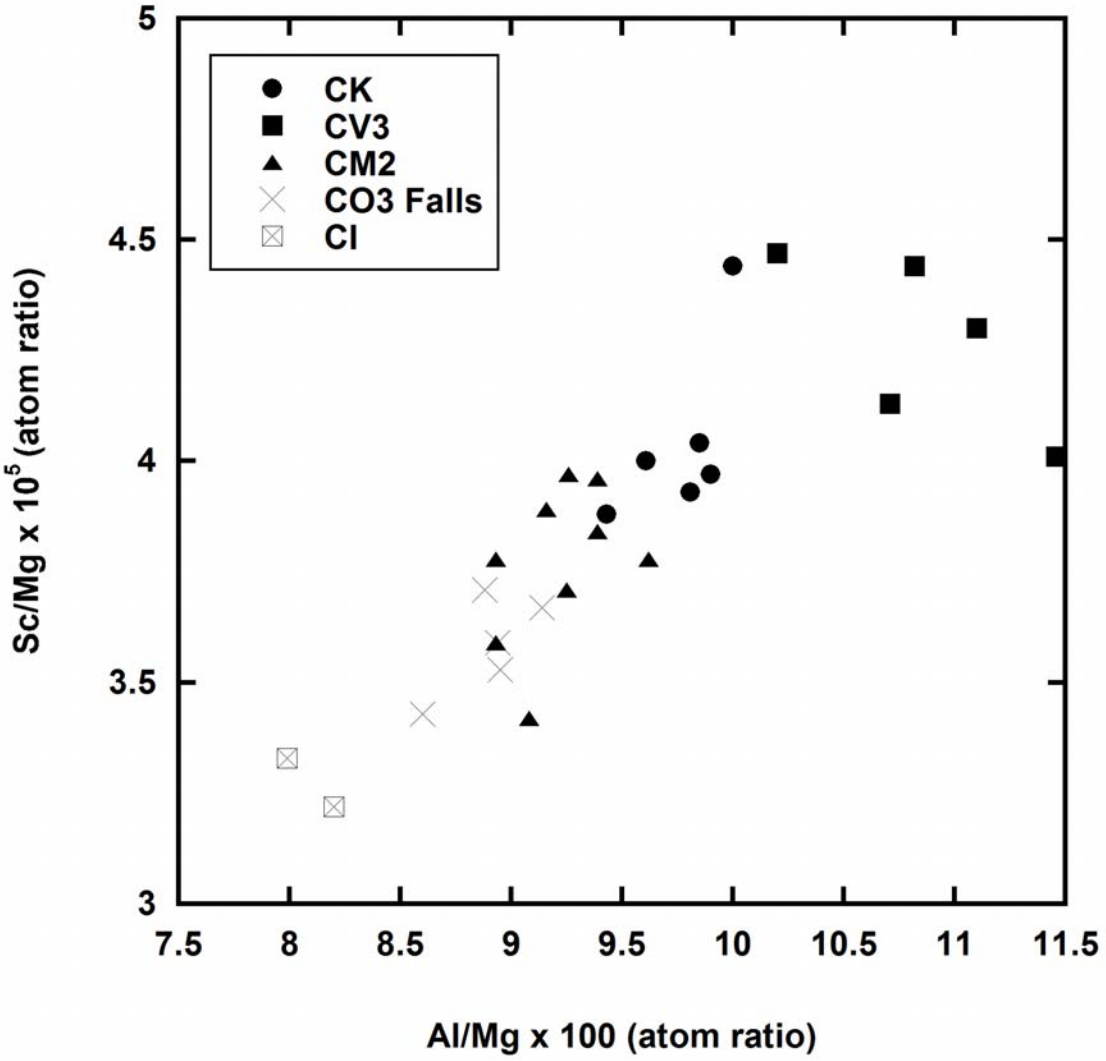


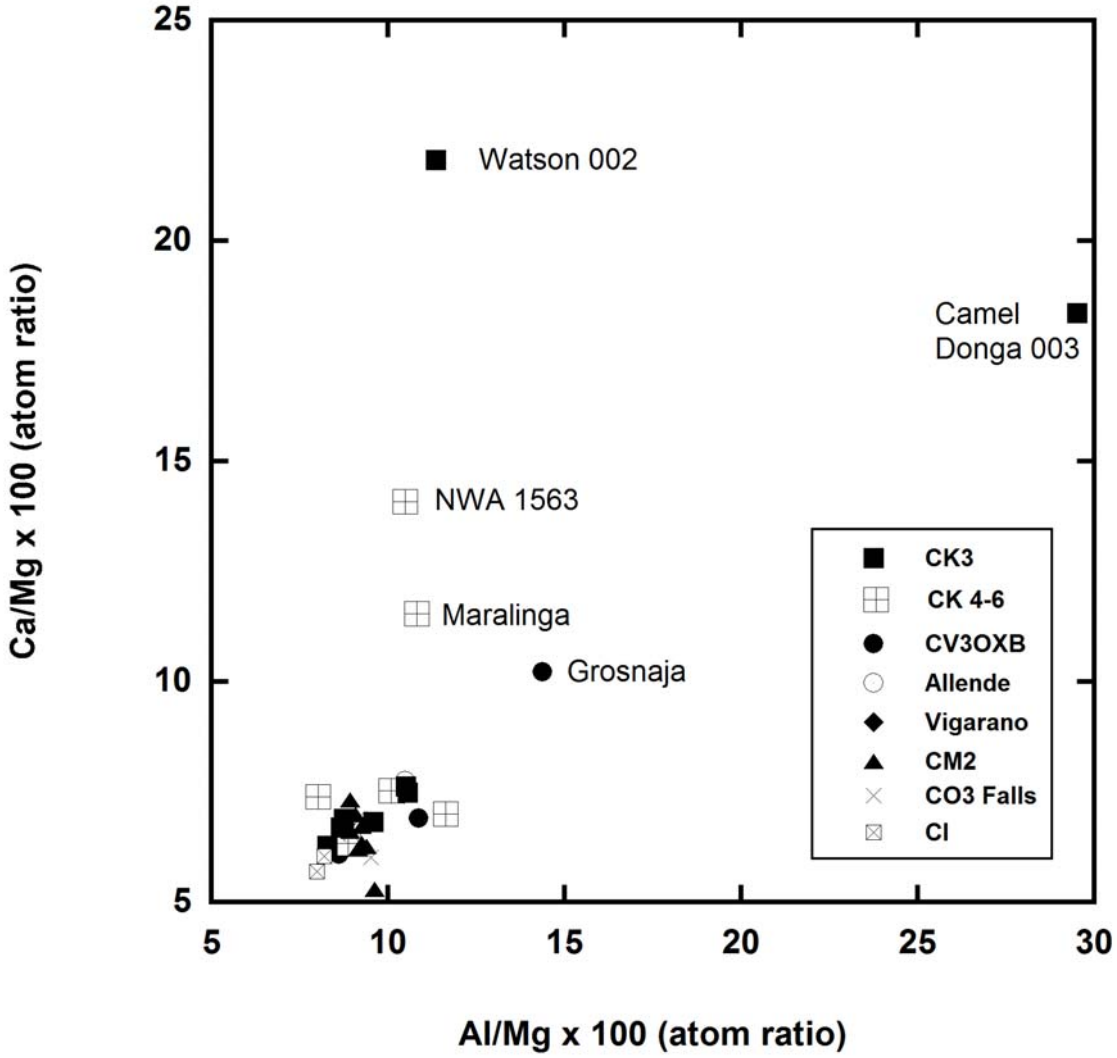


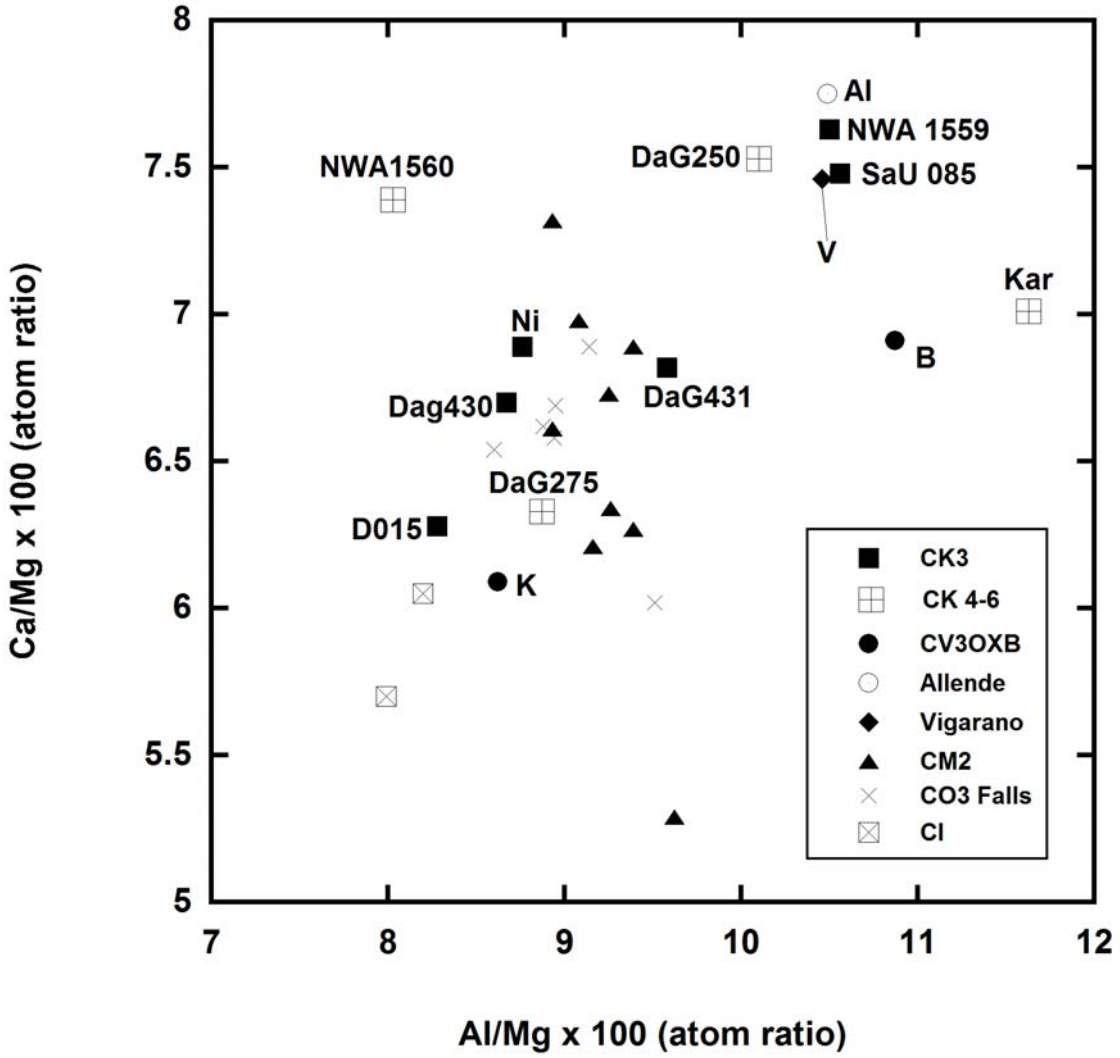


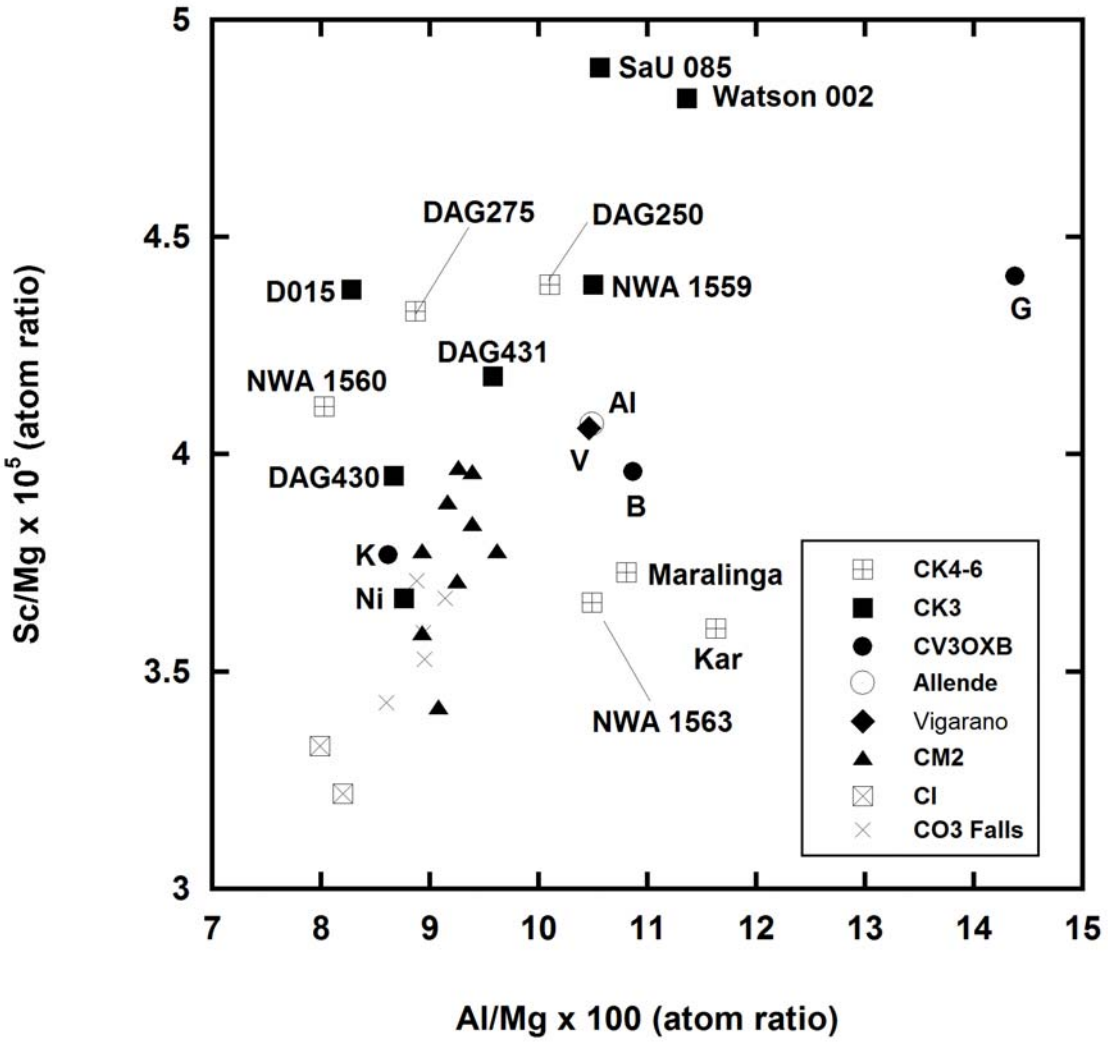


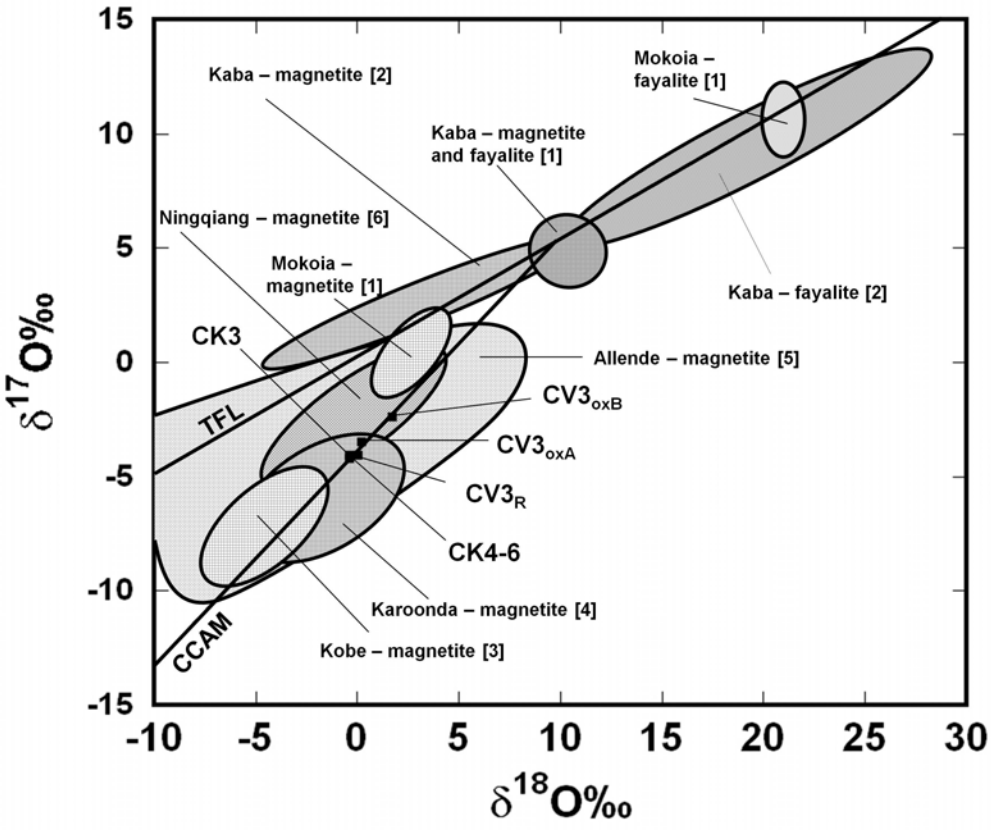


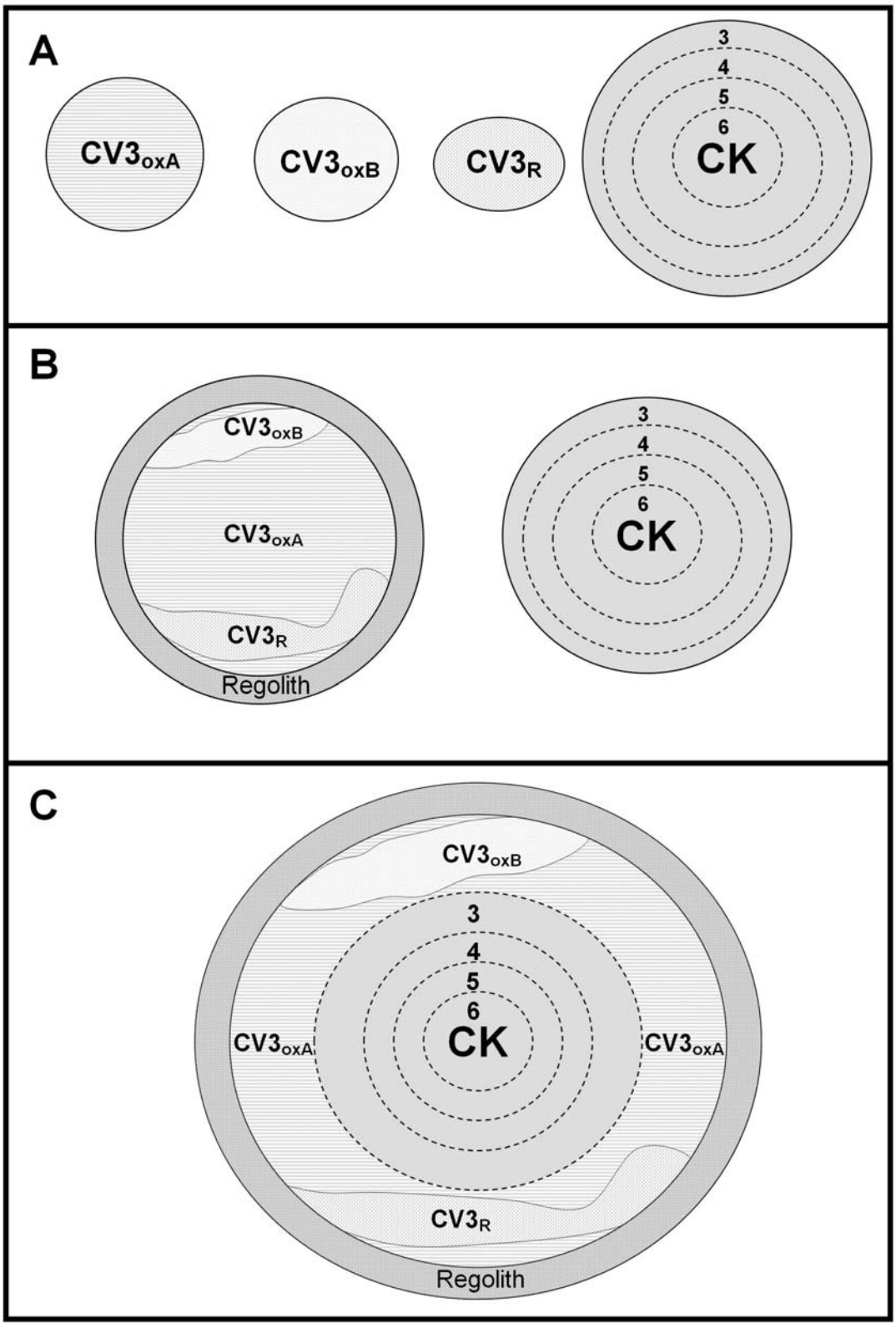








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CK
CV3oxA
CV3oxA
CV3R
Regolith